Renewable and Sustainable Energy Reviews 103 (2019) 423–442

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review on beet sugar industry with a focus on implementation of waste-to-energy strategy for power supply

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A R T I C L E I N F O

Keywords:
Anaerobic digestion
Beet sugar industry
Life cycle assessment
Renewable bioelectricity
Municipal solid waste

A B S T R A C T

Among the various agri-food sub-sectors, sugar production is specifically ranked among the top energy-intensive industries in which massive amounts of various fossil energy carriers are used during sugar beet processing jeopardizing the environmental sustainability of the whole industry. Among the various solutions introduced to date, using renewable energies to supply power to this industry could be regarded as a promising approach to reduce the environmental concerns faced by this sector. In such context, energy from waste could be the most favorable alternative to meet power requirements of the industry. This review paper starts with reviewing the latest situation of sugar production and sugar beet cultivation around the world. Principal sugar beet processing stages as well as different waste-to-energy (WTE) techniques are also reviewed and discussed. In order to evaluate the impacts of the proposed solution, i.e., WTE for power generation in beet sugar industry, two factories located in Iran were considered as case studies and subsequently, the implementation of a kind of waste-oriented electricity as an alternative to fossil-based electricity (conventionally consumed in the factories) was investigated. Moreover, the environmental hotspots in the sugar beet processing factories were determined for further possible improvements. Overall, it was found out that implementing renewable bioelectricity in the studied sugar factories could considerably reduce the environmental burdens; i.e., 14.11–15.41% in human health, 1.49–1.54% in ecosystem quality, 4–4.4% in climate change, and 4.18–4.87% in resources damage categories.

1. Introduction

The adverse environmental impacts of the increasing global dependency on fossil-oriented resources have overshadowed the primary concern associated with the depletion of these energy reserves [1–3]. More specifically, over 80% of the world's energy basket is contributed by fossil fuels, resulting in emission of various substances to the air [4,5]. This has introduced direct serious challenges into the human

Abbreviations: GHG, Greenhouse Gas; UK, United Kingdom; EU, European Union; USA, United States of America; OECD, Organization for Economic Co-operation and Development; MSW, Municipal Solid Waste; LCA, Life Cycle Assessment; ISO, International Sugar Organization; FAO, Food and Agricultural Organization; IFCO, Iranian Fuel Conservation Company; BP, British Petroleum; mtoe, million tones oil equivalent; WTE, Waste-to-Energy; CHP, Combined Heat and Power; LFG, Landfill Gas; AD, Anaerobic Digestion; CH_4, Methane; CO_2, Carbon Dioxide; H_2S, Hydrogen Sulfide; PM, Particulate Matter; H_2, Hydrogen (gaseous form); CO, Carbon Monoxide; C_2H_6, Ethane; C_2H_4, Ethylene; ILCD, International Reference Life Cycle Data System; PCR, Product Category Rules; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; FU, Functional Unit; OB, On Beet; DALY, Disability Adjusted Life Years; SO_2, Sulfur Dioxide; NO_2, Nitrogen Dioxide; MWh, Megawatt Hour; PDF*m^2*yr, Potentially Disappeared Fraction*m^2*year; NO_x, Nitrogen Oxides; SO_x, Sulfur Oxides; CO_2eq, CO_2 equivalent; GW, Global Warming; MJ, Mega Joule; SO_3, Sulfur Trioxide; MW, Megawatt

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https://doi.org/10.1016/j.rser.2018.12.056
Received 16 May 2018; Received in revised form 9 December 2018; Accepted 31 December 2018
Available online 10 January 2019

health sector causing millions of death incidences annually [6]. In addition to that, the increased anthropogenic GHG (greenhouse gas) emissions and their consequent global warming impacts (such as extreme weather conditions, exposure to heat waves, and the resultant economic losses) are arguably among the most grave challenges faced on a worldwide scale in the 21st century [6–9]. These have collectively created a momentum among the policy makers driving them to further focus on improving energy efficiency of energy-intensive industries and reducing their environmental impacts. For instance, UK (United Kingdom), Austria, and some provinces in Canada co-founded the Powering Past Coal Alliance with an aim to expedite climate protection through the swift phase-out of coal-fired electricity [10].

Apart from primary electricity generation, agri-food industry is also among the major energy-consuming sectors while its energy requirements have grown exponentially in response to the population and economic growth, rising consumer incomes, changing technologies, limited supply of agricultural land, and a desire for higher living standards [11,12]. In more detail, this sector is responsible for around one-third of the world's total end-use energy consumption – with more than 70% consumed beyond the farm gate – and is heavily dependent on fossil fuel resources for production, transportation, processing, and distribution [13]. In the year 2013, on average 17% of the EU-27's gross energy consumption (and 25.7% of its final energy consumption) was attributed to cultivation, processing, packaging, and bringing food to European citizens' tables while about 80% of the total energy associated with the entire food life cycle originated from fossil fuels [14]. Detailed data on the share of agri-food industry from the total energy use are indicative of similar conditions around the world, e.g., 14% for France [15], 13% for Sweden [16], 18% for the UK [17], 19% for the USA (United States of America) [18], and around 20% for some OECD (Organization for Economic Co-operation and Development) countries [12]. The major implication of such statistics could be the huge amount of air pollution and the GHG emissions and the consequent threats posed to human health and ecosystem quality by this sector.

Sugar production is one of the most energy-intensive industries under the agri-food sector category [11,19]. Agricultural cultivation, sugar beet processing, and transportation are the major stages consuming energy throughout the life cycle of sugar production. Based on the existing literature, sugar beet processing stage is the most energy-intensive phase of sugar production [20,21]. It should be noted that the energy use issue in the processing stage is of a lesser importance when sugar is produced from sugarcane due to the substitution of fossil fuel by sugarcane bagasse [22]. While on the other hand, cane sugar production bring about some other environmental concerns in terms of high water use and eutrophication compared with the other sources of sugar [20]. Therefore, the huge deal of fossil energy used in the processing stage (except for cane sugar) as well as the traditional environmental threats posed throughout the life cycle of sugar production are the main sustainability challenges faced by this sub-sector. Accordingly, understanding the quantities of energy consumption at different stages and determining waste energy flows can substantially help to identify areas of energy intensity aimed at improving the overall efficiency [23]. Beside energy management and optimization, environmental aspects of the processes involved should also be taken into account.

Many attempts have been made in order to improve the energy and environmental indices in the agricultural stage of sugar production [24–28]. Moreover, some investigation have focused on the energy challenges in the processing stage of sugar factories as well as the energy auditing and optimization of the main energy flows. However, little has been done on the implementation of renewable energies as sources of power generation in sugar production processes. It should be noted that although exploiting bagasse energy for supplying energy requirements in sugar cane factories have been reviewed and assessed [23,29,30], other potentials for the use of renewable energies in this industry have been generally overlooked. Given the key potentials of bioenergy carriers to achieve the goals of sustainability in terms of energy security and climate protection [31], utilizing various renewable energies especially those of waste origins needs to be taken into consideration [32]. However, the environmental aspects of these alterative resources should still be scrutinized through environmental assessment approaches such as LCA (life cycle assessment). LCA is generally defined as a tool capable of evaluating the environmental impacts of a product/service throughout its life cycle [33–35]. In better words, LCA is one of the assessment methods widely used for inspecting the environmental impacts of products [36] and is also the most widely used technique for assessing the environmental balance of renewable energy systems [37,38] and futuristic strategies. The aim of the present review was to comprehensively review and discuss beet sugar industry, its current situation, and related LCA studies. Moreover, utilizing a kind of waste-oriented electricity, i.e., bio-methane derived from organic fraction of MSW (municipal solid waste) for renewable power generation in sugar production chain was analyzed and discussed. To evaluate the impacts of the proposed approach, two case studies using Iran's data were considered and the consequent environmental impacts of employing the proposed solution were calculated using the LCA approach. Besides, the present study was also aimed at assessing the environmental impacts of sugar beet processing phase in Iran for the first time.

2. Sugar production

2.1. Sugar producing materials

Sugar has been a widely used commodity in human daily diet as a source of energy, sweeteners, and preservatives. Sugar or chemically called sucrose is a saccharide quickly broken down through the action of sucrose enzyme into fructose and glucose in the human body [39]. Generally, sugarcane and sugar beet are the major sources of sugar production in the world. Sugarcane cultivation and the techniques used for sugar production probably date back to 2000 B.C. in India while in around 600 A.D., this industry reached Persia (now Iran) where it was further developed, i.e., introduction of sugar purification techniques [39]. Subsequently, the knowledge of sugar production was brought into the Mediterranean regions as a result of the Arab conquests in the 7th century. Nevertheless, due to the tropical nature of sugarcane (i.e., optimal growth taking place at around 35° of the equator), its cultivation in the Europe was only limited to a few countries and the continent was focused on the implementation of sugar refining industry instead, relying on imported raw cane sugar [40].

Contrary to sugarcane, sugar beet cultivation was initiated much more recently in the year 1747 when a German chemist discovered sugar in sugar beet varieties [41]. However, sugar beet was not grown widely in Europe until the 19th century due to the fact that its processing methods were not well developed. Since then, technical improvements in beet processing, quick development in plant breeding methods, agricultural mechanization, fertilizer application as well as trade barriers faced by the sugarcane industry led to substantial increases in sugar beet cultivation throughout the world [42].

It should be noted that cane and beet are different in terms in their respective farming practices caused by the differences in the anatomy and physiology of the plants as well as the geographical and other circumstances under which they are typically grown [42]. Moreover, there are some differences in their composition. More specifically, cane and beet have almost similar sugar contents (typically, 15% vs. 18%, respectively) while they are different in terms of their non-sugars (non-sucroses) and fibers contents. More specifically, beet juice and cane juice contains about 2.5% and 5% non-sugars while their fiber contents stand at about 5% and 10% respectively. Accordingly, these compositional differences necessitate different methods to extract their sugar. Overall and by taking into account the above-mentioned differences between these crops in terms of farming, composition, and processing, the sugar industry has been divided into two moieties, i.e., beet sugar

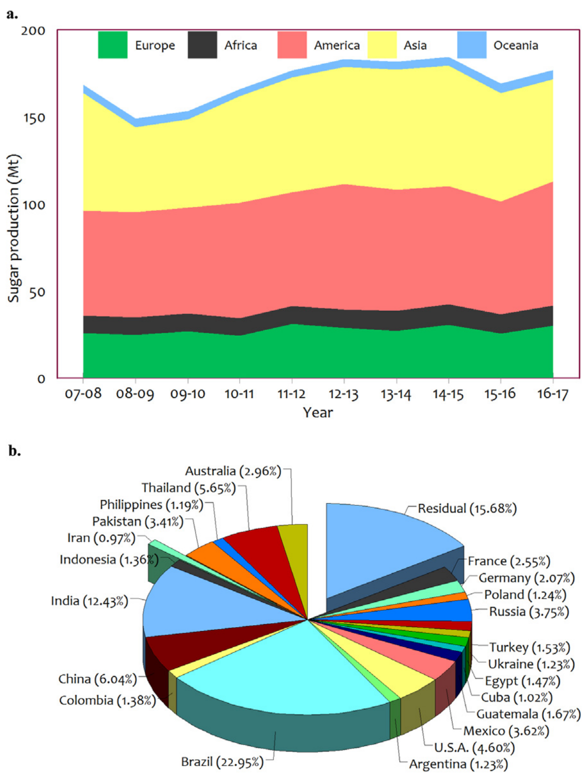

Fig. 1. a. Total sugar production trend in different continents between the years 2007–08 and 2016–17. b. Share of different countries from global sugar production in 2016–17.

industry and cane sugar industry [39].

2.2. Sugar production throughout the world

Based on the report published by the International Sugar & Sweetener, the global production of sugar in 2016–17 stood at 176.9 million tons out of which 39.7 million tons were contributed by sugar beet (22.5% of global sugar production) while the rest of 137.2 million tons were of sugarcane origin (77.5% of global sugar production) [43]. Fig. 1a shows the total sugar production trend in different continents between the years 2007–08 and 2016–17 [43,44]. Based on the data presented in Fig. 1a, in the year 2016–17, America had the highest share from the global sugar production with 59%, followed by Asia (23%), Europe (12%), Africa (5%), and Oceania (2%) [43,44].

Among the main countries which reportedly produced sugar in 2016–17, Brazil and India were the largest producers contributing more than one-third of the global sugar production (Fig. 1b) [43,44]. In fact, these countries along with China, Thailand, and the USA produced more than half of the sugar in the world. These statistics also show that 90 countries in the world had small shares in the total world sugar production, i.e., less than 20% collectively.

Based on the report published by the ISO (International Sugar Organization) [45], global sugar consumption has expanded by 1.93% on average over the past decade, largely driven by rising incomes, population growth, and shifting dietary patterns. Moreover, 67% of the global sugar consumption was registered in the developing countries while these countries especially those located in Asia, are expected to experience further increases in their sugar consumption rates. Overall, the top ten sugar consumers in the world are India followed by EU-28, China, Brazil, USA, Indonesia, Russian Federation, Pakistan, Mexico, and Egypt [45].

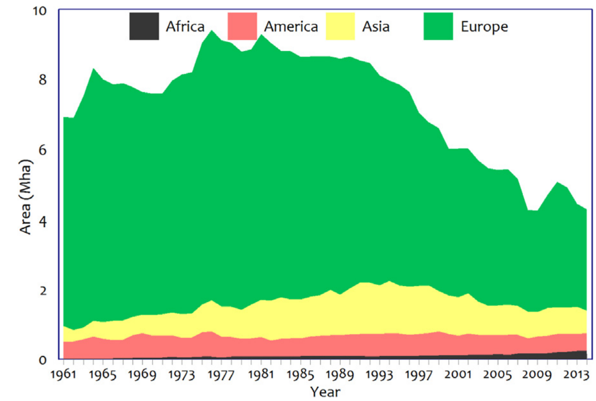

Fig. 2. Changes in sugar beet cultivation in different parts of the world (1961–2014).

2.3. Sugar beet in the world

According to the latest statistics presented by FAO (Food and Agricultural Organization), 54 countries cultivated sugar beet in the year 2014 with a harvested area of 4.47 million hectares and production quantity of 269.7 million tons sugar beet roots (average production quantity of 60.31 t of sugar beet root per hectare) [46]. Nevertheless, the global sugar beet harvested area has been experiencing a decreasing trend since mid-1970s (Fig. 2) [46]. More specifically, the highest rate of sugar beet harvested area took place in the year 1976 in which about 9.4 million hectares sugar beet was cultivated. Since then, the sugar beet harvested area decreased by annual rate of 1.5% till the year 2014 in which the harvested areas decreased to 45% of its initial area in 1976. In 2014, Europe was the leading continent contributing approximately 67% of the global sugar beet harvested areas, followed by Asia (with about 15%), America (with about 11.5%), and Africa (with about 5.9%). In spite of its high share, Europe has experienced the highest rate of reduction in sugar beet harvested area if compared with that of the year 1976.

Comparing the global trend of harvested area and sugar beet root yield (Fig. 3), it can be observed that root yield was increased from 1961 to 2014 by about 160% while on the contrary, sugar beet harvested area experienced a 35.4% decrease during the same period [44]. This observation could be explained by the improvements in sugar beet yield per hectare as a result of advancements in plant breeding methods, agricultural mechanization, and fertilizer application. More specifically, the sugar beet root yield per hectare in 2014 was 2.6 times higher compared with the records reported in the year 1961. Europe (with about 69.8%) followed by Asia (with about 12.8%), America

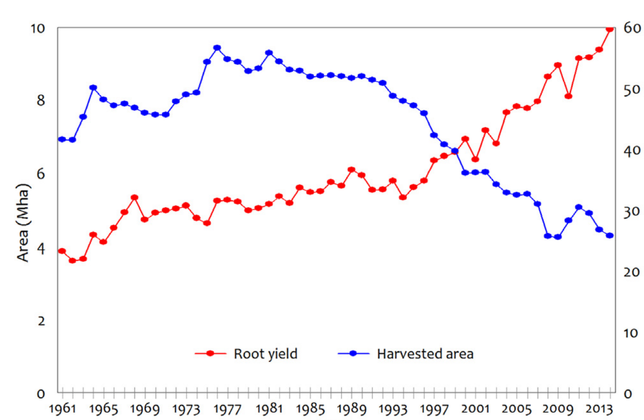

Fig. 3. Changes in global root yield production and sugar beet cultivation area (1961–2014).

Table 1
Countries produce both sugar beet and sugarcane in their cropping system and their amount of sugar production in 2017 [38].

Country	Sugar production (10^3 t)		
	Sugar beet	Sugarcane	Total
China	1088	9600	10688
USA	4632	3510	8142
Pakistan	22	6000	6022
Egypt	1400	1200	2600
Iran	875	850	1725
Japan	544	168	712
Morocco	525	30	555

(with about 12%), and Africa (with about 5.3%) had the highest shares of the global sugar beet root production in the year 2014. Moreover, France, Russia, Germany, USA, Turkey, Ukraine, Poland, Egypt, Great Britain, and China were the top ten sugar beet producers around the world in 2014, contributing over 80% of the world sugar beet root production [44].

2.4. Sugar production in Iran

Among the sugar producing countries, 35 countries only produce sugar beet root and 71 countries only produce sugarcane while only 7 countries produce both crops (Table 1) [44]. Thanks to its climatic and latitude variation, appropriate growth conditions, and well-established sugar processing technology, Iran is one of these countries (along with USA, China, Morocco, Egypt, Japan, and Pakistan).

The total sugar production (excluding imports) in Iran in the year 2016–17 was recorded at 1.72 million tons (Fig. 4) amounting to 0.97% of the global sugar production and 2.94% of the total sugar production in Asia [43]. Out of this quantity, just 875,000 t was of sugar beet origin and 850,000 t was contributed by sugarcane [43]. In spite of the fluctuations recorded between 1961 and 2017, the demands for sugar in the Iranian market have been met by sugar beet, sugarcane, and sugar imports (with average shares of 42.6%, 14.8%, and 42.6%, respectively). Nevertheless, if the statistics reported over the last five years were taken into account, the average shares of sugar beet, sugarcane, and imports would be 27.6%, 27.1% and 45.2%, respectively [44].

Sugar consumption in Iran has also increased from 1961 to 2017 by 34.6% in response to increase in population, industrialization, and changes in diet and eating habits of the Iranian society [44]. More specifically, the per capita consumption of sugar currently stands at 35 kg/person/year [44] which is higher than world average consumption (i.e., approx. 25 kg/person/year) [47].

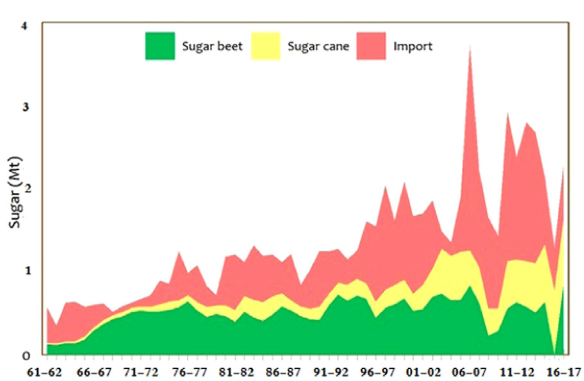

Fig. 4. Sugar supply from different sources in Iran (1961–2017).

2.5. Sugar beet in Iran

Based on the report released by the Iranian Sugar Factories Syndicate, in the year 2014, from the harvested area of about 96350 ha in Iran, 4.7 million tons of sugar beet root was produced with an average production of 48.9 t of sugar beet root per hectare [47]. It should also be noted that Iran's share from the global sugar beet root production in 2014 was 1.7% while its share from global sugar beet harvested area was reported at about 2.2%. This simply implies the lower sugar beet root yield per hectare in Iran, i.e., 48.9 t vs. the global average of 60.31 t sugar beet root yield per hectare. More specifically, the average sugar beet root yield in Iran in 2014 was 8%, 20%, 4%, 21%, and 18% lower than the average sugar beet root yield values registered in Africa, America, Asia, Europe as well as the world, respectively. Based on the FAO statistics, the average yield per hectare in Iran was half of the yields obtained in some of the other sugar beet producing countries such as France, Spain, Switzerland, the Netherlands, Austria, Belgium, Germany, Italy as well as UK [46].

Nevertheless, during the last three years, some successful attempts have been made in order to increase the harvested area as well as sugar beet root yield per hectare in the country. These attempts have led to an increase in the production of sugar beet root to more than 6 million tons in the year 2017 from the harvested area of more than 112,000 ha (average production of 53 t of sugar beet root per hectare). However, it should be noted that the current drought in Iran and water scarcity conditions forecasted for the coming years [48,49] could negatively affect both the harvested area as well as sugar beet root yield per hectare undoing the latest improvements. In this regards, summer cultivation of sugar beet, optimization of irrigation methods, and improving their efficiency are among the most important strategies set forth by the Iranian Ministry of Agriculture.

Currently, there are 12 major sugar beet producing provinces in Iran as listed in Table 2 [47]. The highest sugar beet harvested area in 2017 belonged to East Azerbaijan, Khorasan, Esfahan, Fars, and Kermanshah provinces which also produced more than 75% of Iran's total sugar beet root in the same year. Among all the major sugar beet producers in the country, Khuzestan had the highest sugar beet root yield in 2017, i.e., 61.6 t per hectare, followed by Semnan (55.3 t per hectare), East Azerbaijan (53.5 t per hectare), Lorestan (53.4 t per hectare), and khorasan (50 t per hectare) [44].

3. Beet sugar industry: beet sugar production processes

Principally, the most important goal of each and every stages of the sugar industry is to separate sugar from non-sugar materials with the highest purity [39]. This objective is achievable through a set of

Table 2
Major sugar beet producer provinces in Iran (Cultivation area and sugar beet root yield) in 2017.

State	Area		Root production	
	ha	(%)	ton	(%)
East Azerbaijan	31431	27.86	1682259	29.89
Khorasan	25779	22.85	1287738	22.88
Esfahan	11214	9.94	494495	8.79
Fars	9508	8.43	439150	7.80
Kermanshah	7405	6.56	336346	5.98
Qazvin	5818	5.16	256182	4.55
Khuzestan	5769	5.11	355251	6.31
Hamadan	5600	4.96	259568	4.61
Ardabil	3050	2.70	141550	2.52
Lorestan	2922	2.59	155899	2.77
Chaharmahal and bakhtiari	2662	2.36	128204	2.28
Semnan	1640	1.45	90602	1.61
Total	112798	100	5627244	100

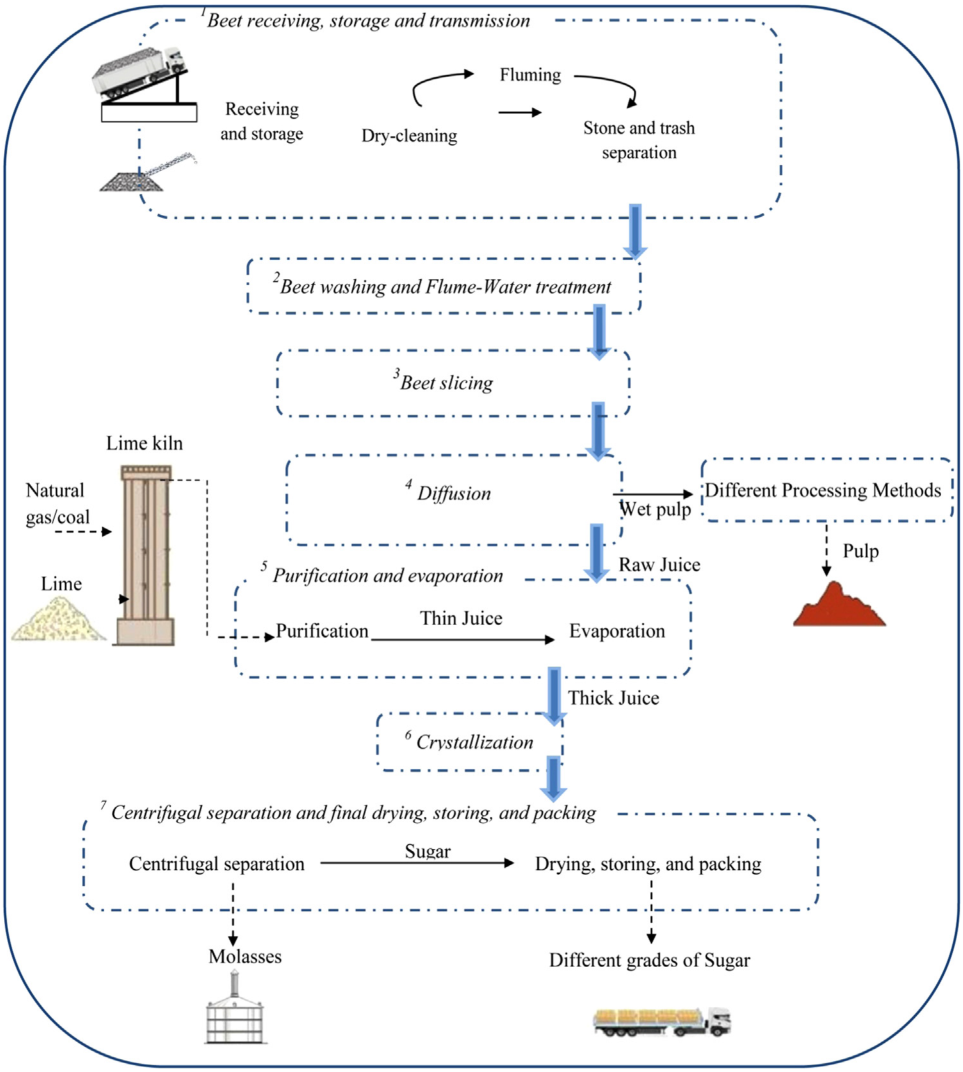

Fig. 5. General layout of beet sugar industry and different stages involved (adopted from [39]).

consecutive operations in several stations at a factory, gradually increasing the purity of sugar (sugar content as % of dry substance) to the highest possible degree. Therefore, the purity of the product leaving each stage of production determines the improvements made throughout that specific stage. In addition to the significance of sugar purity in the overall economics of the sugar production process, the sugar industry has also been increasingly focused on using by-products and waste streams in order to generate value-added products such as ethanol, biopolymers, biogas, fertilizer, heat, etc. [21,50–56]. The general layout of a beet sugar factory is presented in Fig. 5 and is explained in the subsequent sections.

3.1. Beet receiving, storage, and transmission

Generally, beet receiving and storage unit is the starting point of sugar beet processing and is also an important unit in factories mainly due to its effect on separation of tar (i.e., impurities such as soil, sand, clay, stone, leaves, and weeds) as well as on sugar/mass loss during storage. This unit mainly consists of weighing equipment, unloading units (unloading sugar beets from the vehicles), beet sampling, and beet-storage. There are differences in the unloading, sampling, and storage methods practiced by different factories which have been further elaborated in the literature [39].

Following beet receiving and storage unit, there are several other units called dry-cleaning, conveying, and stone-trash separation units. Dry-cleaning (if any) is mainly performed when the beets are transmitted from the storage unit to the main processing line of the factory, with the aim of pre-cleaning the roots in order to remove the tar materials [39]. These operations would consequently reduce the risks of damage to equipment, reduce water consumption, and finally the cost of the process. The conveying unit is to transport beet roots from the storage area to the next stage, i.e., stone-trash (leaves and weeds) separation. In the next stage, the water-beet-stone-trash mixture is introduced into a beet flume and the stones and trash are separated. A beet flume is a U-shaped channel for transporting beets by the means of water [39].

3.2. Beet washing and flume-water treatment

Beet washing is an essential cleaning stage and is technically the last point for removing the soil stuck to the beets as well as the residual stones, weeds, etc. [57]. More specifically, after partially washing the beet roots and separation of stones and trash in the previous stages, the beets transported through a beet flume will then be subjected to the final cleaning in this unit. Arm washer, drum washer, and spray washer are the most common types of beet washers used in sugar factories [39]. This unit plays an important role in supplying a steady flow of clean feedstock to the next stage, i.e., slicing station. It is also worth

mentioning that Flume-Water treatment is the activity of discharging and subsequent cleaning of the flume water from beet washer.

3.3. Beet slicing

In this stage, the cleaned beets are cut into long, thin strips called as “cossettes”. This could facilitate and maximize further sucrose extraction from beets in the next stage, i.e., diffusion. The main components of this unit generally include a beet conveyor, beet hopper, slicers, and knife maintenance shop (for sharpening the slicers’ knives) [39]. Due to the fact that the size and quality of cossettes or in better words, the quality of slicing process would affect the purity of the extracted juice in the next stage, therefore, this stage is one of the most important stages in the sugar production process.

3.4. Diffusion (juice extraction)

The resultant cossettes from the slicing stage are fed into a rotating or tower drum diffuser in which the juice is extracted from the beet cells by a counter current diffusion process. More specifically, when the cossettes are kept in contact with hot water (about 70 °C) in the diffuser, the beet cells are destructed and this phenomenon would facilitate the movement of sugar (sucrose) and non-sugars (non-sucroses) from the cossettes, consequently generating a concentrated solution of impure sucrose, known as raw juice. Typically, raw juice obtained from the diffusion stage contains around 14–15% dry substance (with the purity of 80–85% and 0.5–1.5% insoluble substances) [39,42]. The outlet raw juice is then sent to the next stage, i.e., purification stage, while the spent cossettes (which have gradually lost almost 98% of their sucrose) are fed into large screw presses in order to extract residual juice. The remaining de-sugared solid material after this process is called wet pulp, which is sent to another unit for further processing and possible pressing and/or drying and pelletizing enabling the pulp to be sold as a by-product of the factory. This by-product is usually used as animal feed due to its appropriate amount of proteins and carbohydrates as well as minerals [39]. Overall, the sugar beet pulp processing is an energy-intensive process which undermines the economic profitability of selling pulp as animal feed especially in parts of the world where the value of feed is low while the energy cost is high [58]. In such context and based on the concepts of biorefinery and bio-based economy, pulp could be diverted toward the production of other value-added products rather than being used as animal feed only. For instance, as an attractive option, sugar beet pulp could be used as a feedstock for producing fuel ethanol through biological pathways [58]. Alternatively and as proposed by Alkaya and Demirer [54], sugar beet pulp could be used as a promising feedstock for biogas production through AD in co-digestion with wastewater from the same factory. There are many other applications of sugar beet pulp as well which could also be implemented within the biorefinery framework. Those include the production of cellulose nanofibers from de-pectinated sugar beet pulp [59], biosynthesis of gold nanowires/nanoparticles using sugar beet pulp [60,61], production of pectin and pectic-oligosaccharides as a potential source for functional carbohydrates [62], and extraction of natural antioxidants from pulp for use in vegetable oils [63]. It is also worth mentioning that apart from the different equipment and technologies used in different sugar factories, different methods of wet pulp processing could also lead to differences in the handling procedure used for the co-products generated. For example, Spoerri and Kaegi [21] introduced seven different factory setups in Europe highlighting their differences in terms of co-products handling (Fig. 6).

3.5. Purification (clarification) and evaporation

Purification is considered as the heart of sugar factories due to its impacts on sugar yield, sugar quality, and operation of equipment in the subsequent stages [39]. In this stage, non-sugars, suspended particles, and colloids are removed from the diffusion juice and its pH is adjusted. The purification finally leads to the production of the thin juice, a highly-pure, colloid-free, and low-color juice with minimum hardness (limesalts). More specifically, milk of lime is used to treat heated raw juice in a few steps in order to precipitate and destabilize the non-sugar materials. In addition, carbon dioxide is bubbled through juice in order to precipitate the lime as calcium carbonate and also to adjust the pH and alkalinity of the juice [42]. The resultant thin juice (after sedimentation and filtration) is sent to the next stage, i.e., evaporation, while precipitated calcium carbonate is separated from the juice during the purification process. The calcium carbonate will then be sent to the filter presses or rotary-drum filters for de-watering and is finally sold as carbonation-lime residue. This by-product is one of the by-products of the sugar factories commonly used as soil fertilizer or as pH adjuster. However, some factories discharge carbonation-lime residues in lime ponds of the factories or open dumping sites which is not an environmentally-friendly approach [39].

After purification, the thin juice is still dilute and needs further concentration (by boiling) prior to crystallization. This takes place in the evaporation stage where the thin juice is passed through multiple-effect evaporators [42] turning into a thickened juice with about 60% dry substance and about 8.7 pH, also called thick juice [39].

3.6. Crystallization

The aim of this stage is to considerably increase the purity of the juice to 99.9%, i.e., leaving most of the impurities in the in the syrup (known as mother liquor) and producing sugar crystals from the pure solute. In this regards, beet sugar factories generally employ a three-stage crystallization process through which “boiling” the mother liquor (concentrated juice) occurs in vacuum pans. While the market-quality sugar is only produced during the first stage (after centrifugal separation though), the raw sugars produced during the second and third stages, are dissolved in the thick juice to produce the standard liquor. This liquor is used to feed the first stage of crystallization. It is also worth quoting that the mother liquor of the third stage is called molasses (contains sugar), considered as the largest loss in a sugar factory (i.e., loss of sugar into molasses). Due to its high viscosity and non-sugar content, molasses is difficult to be crystallized. Therefore, it is separated from the system to prevent accumulation of non-sugars (impurities) and is then send to molasses’ tanks for storage and sold as a by-product of the factory [39,42]. Molasses as the most valuable by-product of the sugar factory has a series of applications in yeast fermentation, pharmaceutical, and animal feed industries [39]. Nevertheless, based on the biorefinery and bio-based economy concepts, molasses could also be used for the production of some other value-added products, rather the being used in the-above mentioned industries only. For example, molasses could be used as a feedstock for fuel ethanol production in order to be used in the transportation sector [64,65]. This could, in a consequential manner, contributes to reducing gasoline consumption as well as associated economic and environmental impacts [64,66]. Samorì et al. [67] also suggested the production of some acid catalysts through the pyrolysis of sugar beet molasses. Such catalysts could be used in the esterification of fatty acids with methanol for producing biodiesel as the later stage. In another study, Gao et al. [68] introduced sugar beet molasses as a grinding aid in blended cements improving their compressive strength. There are many other applications of molasses, which could also be implemented within the biorefinery framework. Those include using molasses in paddy soil in order to absorb cadmium and arsenic [69], as a feedstock for AD (in co-digestion with sewage sludge) to produce biogas [70], and as a whole medium for biosurfactants production [71].

3.7. Centrifugal separation and final drying, storing, and packing

The product of crystallization stage called “massecuite” is a mixture

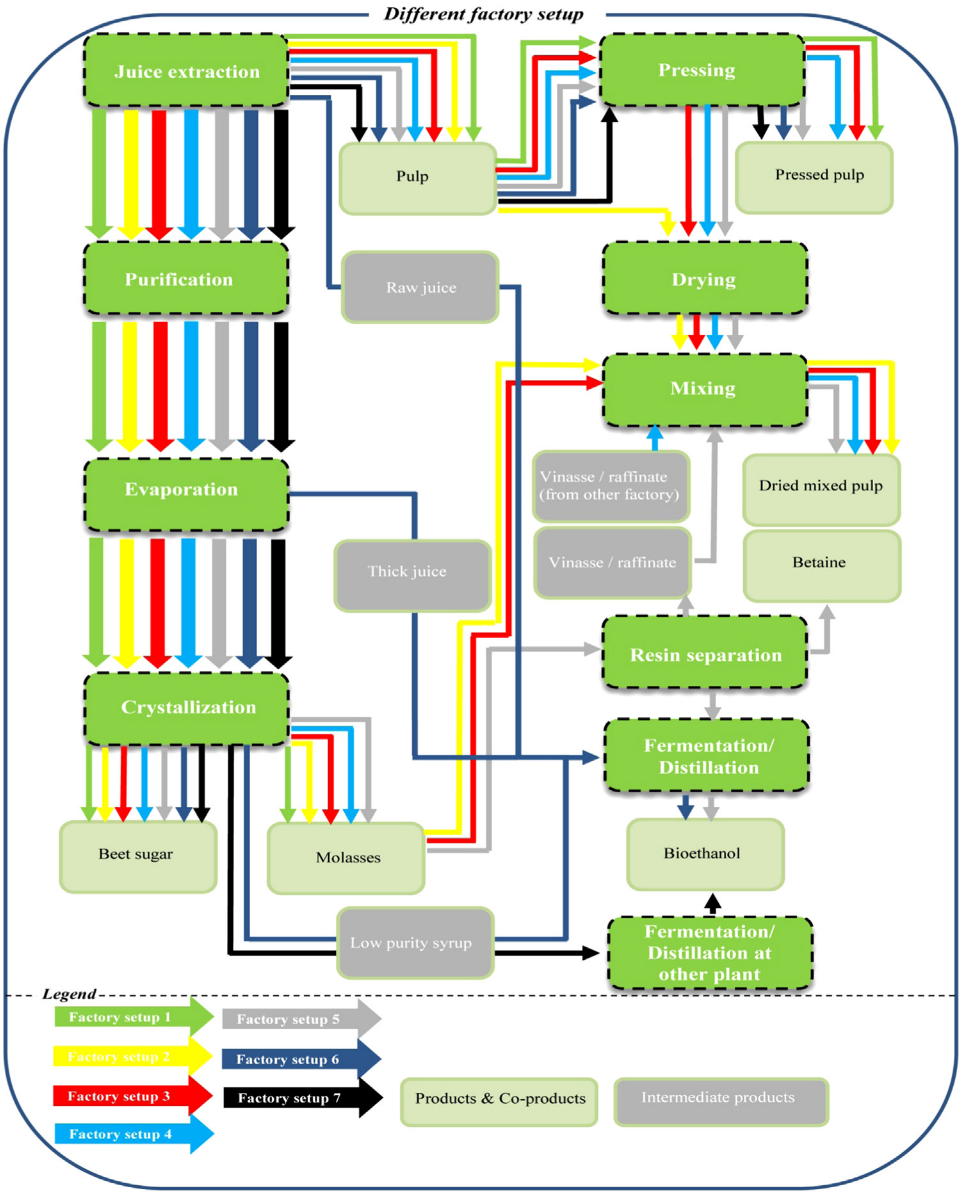

Fig. 6. Simplified schemes of different factory setups in the Europe (adopted from [21]).

consisting of crystals that are still bound to the mother liquor. Therefore, centrifugal separation is needed for the separation of sugar crystals. The output of this stage is sugar which is sent to the next station, i.e., drying, storing, and packing. Another output is molasses (sent to molasses' tanks). The wet sugar obtained from the centrifugal station is first dried in a sugar dryer and is then sent to the sorting unit for grading and final packaging. In some factories, the dried sugar may be sent directly to silos or will be processed into the specialty sugars [23,39].

3.8. Beet sugar industry in Iran: a brief description

The history of the beet sugar industry in Iran dates back to 1894 when the first sugar (from beet) factory started to operate [72]. Ever since, many leading countries in beet sugar industry such as Germany, France, and Poland established factories in different regions in Iran. However, these factories have failed to perform necessary technological updates over time. This issue in combination with the low price of fossil energy carriers in Iran have caused the beet sugar industry to be considerably more energy-intensive in comparison with its counterparts in the world. In an attempt to address this challenge, the Iranian government imposed a policy aiming at replacing fuel oil with natural gas as the main energy carrier of the industry [11]. As a result, the share of fuel oil from the total fuel consumption in the country's sugar industries decreased from 73% in 2002–03 to 39% in 2016–17 while the share of natural gas increased from 23% to 56% over the same period [11,73]. In 2016–17, among the 35 beet sugar factories in existence, only 26 factories were operational which produced about 875,000 t sugar in the respective year.

Among the most important attempts made in reducing fossil energy consumption by the beet sugar industry (in addition to the mentioned shift toward natural gas) were to 1) compile energy consumption standards in the sugar industry, 2) audit energy consumption and implement efficient energy management strategies in the industry, and 3) increase the level of knowledge of sugar technologists in the context of efficient use of energy [73]. Moreover, many factories updated their technologies to the latest technologies available in Europe under the evaluation and supervision of German or French experts. Nevertheless, based on the report published by the IFCO (Iranian Fuel Conservation Company) in the year 2017, the sugar industry in Iran is still the main

energy-intensive industry among agri-food industry sub-sectors [73]. On the other hand, primary electricity generation in the Iranian power plants is mainly dependent on fossil fuel resources (i.e., at least 93.2% of Iranian electricity generation is fossil-based) [74]. Therefore, the issue of considerable electricity consumption by the sugar beet industry and the implementation of strategies to reduce/optimize such high energy consumption could be of critical importance. This necessitates the exploration of various potentials in order to integrate renewable energies into the existing plants.

It is also worth mentioning that, despite all the attempts made in reducing fossil energy consumption in Iran's sugar industry, to the best of our knowledge, there has been no study on LCA of sugar production in Iran especially with a focus on the factory stage. Providing in-detail assessments in this domain could provide sugar factories and sugar technologists with guidelines on identifying the environmental hotspots in their production process as well as on comprehending the effects of their decisions on the environmental balance of the respective factories.

4. Implementation of WTE for power generation in sugar beet industry

Based on the latest report published by BP (British Petroleum), the world primary energy consumption in 2016 stood at staggering 13276.3 mtoe (million tones oil equivalent) -with a growth rate of 1% compared with 2015- out of which more than 85% was originated from fossil fuel resources [75]. In the same year, the share of the power oriented from renewable resources (excluding hydro) reached 53 mtoe, experiencing the largest increment on record with a growth rate of 14.1% compared with 2015 [75]. Increasing global interest in renewable power generation is mainly due to the sustainable nature of these alternative energy carriers [8] as well as their role in improving energy security [76,77] while reducing environmental pollutions (including GHG emissions) over their fossil-oriented counterparts [78,79]. In this context, developing power generation (especially electricity) from different renewable energy sources could be a promising option to be implemented by the sugar beet industry to not only reduce the currently high dependence of this industry on fossil energy carriers but also to provide additional environmental benefits [80–82]. On such basis, the integration of electricity generation from MSW into the sugar beet industry is analyzed and discussed in the subsequent section.

4.1. Electricity generation from MSW using different waste treatment methods

Urbanization, fast population growth, alongside huge industrial and economic developments all have been mentioned as major drivers of more material consumption and consequently, increased MSW throughout the world [83]. Such increasing trend in MSW generation globally is expected to continue, rising from 1.3 billion metric tons to approximately 2.2 billion tons between 2012 and 2025 [84]. This huge increase in MSW generation could pose many environmental and social threats turning municipal waste management into a global challenge. While on the other hand, MSW management could also be regarded as an opportunity if sustainable and cleaner approaches are adopted. In better words, conversion of MSW into energy through the so-called WTE platform could be a potentially sustainable and environmentally-friendly solution to deal with this growing challenge [85]. In fact, WTE technologies could simultaneously offer a number of benefits such as reducing the land pressure problem in urban areas, efficient management of wastes, and providing energy in an eco-friendly and economically-viable manner [74,86].

WTE technologies basically involve biological and thermal processes in order to extract the energy stored in waste streams, e.g., MSW, to generate electricity, heat or both (also known as CHP-combined heat and power) [87]. From the pathway point of view, different WTE technologies generally encompass LFG (landfill gas) recovery, AD (anaerobic digestion), incineration, gasification, and pyrolysis.

LFG emissions from landfills have been reported as the main contributor to GHG emissions originated from the waste and wastewater management sector [88]. In this regard, collecting LFG and exploiting its energy could help with reducing GHG emissions and providing energy simultaneously. LFG recovery technique is a well-established technology for electricity (or heat) generation from waste through capturing the gaseous mixture obtained through the biological decomposition of landfill materials [89]. The amount of gas produced can be estimated using different methods and software [90–95]. It is also worth mentioning that this technique mainly requires a well-engineered landfill capable of maximal capture of LFG and collecting leachate. Nevertheless, some traditional landfills are currently equipped with LFG recovery but lack a proper leachate collection system.

It is also worth quoting that value-added products such as hydrogen and sulfur could be extracted when refining LFG. In a study conducted by Heo et al. [96], a techno-economic analysis based on process simulation and economic analysis was performed in which the production of H_2 from LFG in Republic of Korea was investigated. The process started with the LFG desulfurization process in order to remove H_2S. The LFG was then fed into an absorption unit for CO_2 absorption. The resultant medium-grade LFG (~70% methane) was then sent to a membrane reactor (instead of being used in a packed bed reactor as the conventional approach) for further processing and producing H_2 for various applications. The results of process simulation confirmed that using a membrane reactor could effectively improve methane conversions (0.5–16.4%) as well as H_2 yields compared with a packed bed reactor. Moreover, the output of the economic analysis showed 34% reduction in H_2 production costs when using a membrane reactor (9.72 vs. 6.46 US$/kg H_2) for a packed bed reactor and a membrane reactor, respectively) [96]. In a similar study conducted by Heo et al. [97], a techno-economic analysis was performed for producing sulfur from LFG through a biological desulfurization process in Republic of Korea. The results showed that a lower NaOH flow rate (0.5–1.0 m^3/h) could exert a stronger effect on sulfur production compared with higher dosages (1.5–2.5 m^3/h); showing possible cost savings by avoiding excessive usage of NaOH. Moreover, economic profitability of the biological desulfurization process could be achieved during discounted payback periods of 5.7–6.9 years for discount rates of 2–10% in a 10-year project (considering revenues from sulfur sales as well as local heat supply [97]. It should also be noted that assessing the potentials of using LFG recovery in conventional landfills, optimization of landfill gas collection, optimization of electricity generation from LFG as well as evaluating the environmental and economic aspects of LFG recovery have also been taken into account [98–102].

AD is the process of converting organic fraction of MSWs into biogas and digestate (value added products) through a microbial decomposition in an oxygen-free environment. The produced biogas (mainly consisting of CH_4 and CO_2), after eliminating its impurities (such as CO_2, H_2S, water, and some other minor constituents) could be converted into electricity/heat. This could be achieved through bio-methane combustion in CHP engines, internal combustion engines, boilers, kitchen stoves and/or introducing it to the natural gas grid [74,103].

The produced digestate which consists of semi-solid residues could be employed as an agricultural fertilizer after some treatment (normally through composting). It is important to note that AD should be designed and performed in an environmentally favorable and techno-economically profitable manner. Accordingly, in a techno-economic study, Rajendran et al. [104] simulated biogas production from the organic fraction of the MSW under six different scenarios based on industrial data. The results showed that the profits made by AD of organic fraction of MSW under the studied scenarios depended on annual production capacity of the plant, the efficiency of upgrading technology as well as on the net energy consumption in the plant. Moreover, increasing the annual processing capacities of the MSW could result in high net present value as an economic index. The study also suggested integrating

the biogas produced in a wastewater treatment plant with the upgrading unit (water scrubbing and/or the carbon dioxide absorption by amine) as the most economical and profitable investment [104]. The environmental and techno-economic aspects as well as the other aspects of electricity generation through the AD technique have also been vastly studied in the literature [105–110].

Through waste incineration technology; energy recovery, waste volume reduction as well as GHG emission reduction could be effectively realized [111]. Such favorable attributes have collectively made this technique a widespread WTE technology used around the world. In waste incineration, the combustible wastes are burned through a controlled process and converted into heat/steam, flue gas, and ash [112]. The produced heat/steam could potentially be used for electricity generation, district heating, or to supply steam to industrial customers [74]. In spite of its unique features, the most controversial issue associated with its application concerns the proper management of the residues remained post waste incineration process [113], e.g., ash, PM (particulate matter), gaseous pollutants, and dangerous substances such as dioxins and furans as well as toxic heavy metals [114]. Different aspects of waste incineration such as latest technological developments [115,116], electricity generation potential from incineration [117,118], economic and techno-economic assessments [119,120], and environmental impact assessment [121,122] have been well investigated previously.

Pyrolysis and gasification are thermochemical conversion technologies for waste materials. Although they are comparatively considered as emerging technologies in the waste management sector, pyrolysis and gasification have been in use in the other industries for many years, e.g., power industry, petrochemical industry as well as for fuel production purposes [74]. In the pyrolysis process, carbon-rich materials are subjected to thermochemical decomposition (in the absence of oxygen) and are finally turned into a medium calorific gas, liquid, and char fraction [123]. More specifically, the three major products from pyrolysis are *gas stream* (which is the uncondensed gases from the process) mainly consisting of CH_4, H_2, CO_2, CO, C_2H_6, and C_2H_4; *tar/oil* (which is the condensed gases from the process) mainly containing methane, acetic acid, acetone; and *char-pure carbon*, which mainly includes heavy metals and other inert materials [74]. Vochozka et al. [124] presented techno-economic analysis of different WTE technologies including AD (also accelerated by steam-explosion), combustion, and pyrolysis for energy utilization from waste paper in a pilot scale. The results revealed that it was more profitable to treat waste paper using commercial pyrolysis compared to recycling for raw materials production. This simply showed the promising potentials for investment in the area of pyrolysis especially for waste streams. In another study, techno-economic aspect of a Pyro-CHP plant (a plant converting organic fraction of MSW to energy by means of an integrated intermediate pyrolysis and a CHP generator) in the UK was comprehensively analyzed [125]. The results showed that by providing 5 t/h feedstock processing capacity for a Pyro-CHP plant, 4.4 MW electrical power and 5.3 MW thermal energy could be supplied (overall CHP efficiency of 59.7%; electrical efficiency of 27.2%). Moreover, the results of the economic analysis also showed that the capital investment and levelised cost electricity for the mentioned capacity of the plant was estimated as £ 27.64 million and £ 0.063/kWh, respectively. Such electricity generation cost (i.e., £ 0.063/kWh) could reportedly embrace the range of cost defined by the UK government [125].

In the gasification process, carbonaceous wastes are subjected to a heating process (under an atmospheric condition in which the oxygen content has been slightly reduced) [126] and are finally turned into fuel or *syngas*. Both *gas stream* from pyrolysis as well as *syngas* (or fuel) from gasification could be used for electricity generation. A gasification system operating on wastewater sludge was designed and simulated by Lumley et al. [127] and the techno-economic aspects of the system were investigated. The technical results obtained indicated that the system could be practically operated using currently available technologies. The findings also revealed a greater electrical efficiency when using an air-blown gasification compared with AD. The output of the economic analysis showed that by providing raw sewage flows above 0.093 m^3/s (2.1 million gallons/day), a higher profit of up to US$ 3.5 million *vs.* thermal drying and landfill disposal (as an alternative) could be achievable, implying the economic feasibility and profitability of a gasification-based power system [127]. Moreover, pyrolysis and gasification could also be performed through a two-stage pyrolysis–gasification system [128]. It is worth quoting that using pyrolysis and gasification technologies for MSW treatment at commercial scale still requires further developments [129–134]. In a comprehensive study conducted by Luz et al. [135], the technical and economical facets of electricity generation from MSW using gasification process in Brazil was analyzed under different scenarios. Based on the results obtained, a hypothetic gasification plant was capable of generating 794, 905, and 1065 kW/ton MSW for a population of 34,203 (Scenario 2), 60,714 (Scenario 1), and 259,845 (Scenario 3) inhabitants, respectively. Moreover, it was concluded that installing bigger units could increase the economic feasibility due to decreasing the specific costs and increasing the benefit margin. Luz et al. [135] also mentioned that building such plants would severely depend on incentives from governments, even when having a positive net present value. Similarly, Yang et al. [125] also mentioned the importance of governments' and policy makers' acts and supports in achieving the economic profitability of pyrolysis projects. Such conclusions show the significant role of governments and policymakers in the economic viability of pyrolysis/gasification projects.

4.2. Waste generation and management in Iran

Iran is one of the developing countries and is ranked second among the main Middle Eastern economies. The country benefits from large amounts of oil and gas reserves [136] which have led to a huge deal of fossil fuels consumption [137]. This has brought about many environmental problems mainly in the country's major metropolitan regions. Moreover, population growth alongside growing urbanization have also led to an increase in the amount of waste generation in Iran which are generally treated using traditional waste management options, i.e., dumping, landfilling (without LFG recovery and leachate treatment), and open burning. These traditional and inefficient waste management strategies have intensified the many existing environmental problems. Therefore, MSW management has been regarded as one of the most challenging internal issues faced by the authorities over the last decade [74].

Based on the latest available data on waste generation in Iran, more than 15.6 million tons of MSW was produced in urban areas with the population of 55.5 million inhabitants in the year 2014 [74]. The total waste generated in this year showed a considerably high boost of 50.9% compared with the statistics reported in the year 2002 (Fig. 7a). It is worth mentioning that the amount of waste generated in the country peaked in 2007 with 16 million tons of wastes generation. This was 54% and 2.3% higher than the waste generation values reported for the years 2002 and 2014, respectively. Such fluctuations in waste generation could highlight the impacts of other factors on waste generation rate rather than increasing the population solely [74]. The most notable issue is that although the average MSW generation per capita in Iran (i.e., 0.7 kg/person. day) was lower than that of global average (i.e., about 1.2 kg/person. day), but the quality of the MSW treatment activities in Iran did not meet the world's quality standards, leading to serious environmental problems. For example, landfilling was the major waste treatment option in Iran with the share of 71% from the total generated MSW in 2014 (Fig. 7b) while none of these landfills (except those that recently implemented in Shiraz and Mashhad metropolitans' landfills) were equipped with LFG recovery and leachate treatment systems. Composting came as the second option with a treatment share of 24.3% of the total generated MSW in 2014 (Fig. 7b) while the

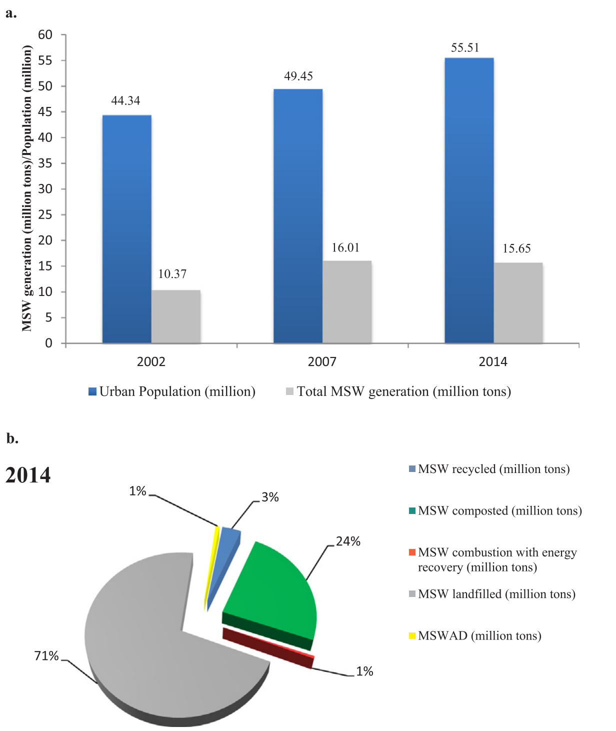

Fig. 7. a) Urban population as well as the amount of MSWs generated in Iran between 2002 and 2014. b) Share of various MSW treatment options (%) in Iran (2014) [74].

average organic material content stood at about 70% (Table 3). Most importantly, the rate of recycling in Iran, i.e., 3% of the total generated MSW in 2014 was still lower than those of the developed countries. This indicates that a great quantity of valuable materials end-up in landfills without recycling or energy recovery. On the other hand, WTE technologies have been recently implemented in Iran and currently have a very limited share in total MSW management sector. For instance, based on the available statistics, only 0.7% and 0.5% of the total MSW generated in 2014 were treated by the AD and incineration techniques (Fig. 7b). There were no reports on the application/operation of pyrolysis–gasification facilities by the Iranian municipalities in the same year.

Considering the growing intensification of the problems associated with inefficient and traditional waste management options in Iran, various waste management technologies especially WTE options have been promoted by the government through the introduction of a number of incentives such as guaranteed renewable electricity purchase tariffs, etc. [74]. Nevertheless, given the fact that the major component of MSW in different provinces in Iran is of organic nature (Table 3) [74], therefore, among the available WTE options, AD would be more preferable. Accordingly, in this study, the potential of electricity generation using AD technique was considered as a promising renewable option for power supply in Iran's beet sugar factories.

5. LCA (Life cycle assessment)

Environmental aspects of sugar processing in sugar factories as well as the potential impacts of renewable energies (as well as WTE) implementation to supply electricity could be scrutinized by LCA. In fact, LCA is capable of quantitatively compiling and evaluating the potential

Table 3
MSW composition in different provinces of Iran*.

Province	Organic	Plastic	PET	Glass	Textiles	Ferrous metals**	Non-Ferrous metals	Paper/ Cardboard	Hazardous	Wood	Leather	C&D	Other
Ardabil	60.1	10	1.1	1.3	4.8	2	0.1	13.8	0.4	1.3	1.4	1.7	2.0
Alborz	73.4	4.8	1.2	1.4	3.9	1.9	0.4	4.9	0.3	1.8	1.6	1.6	2.8
Bushehr	78.8	4	0.4	1.4	1.2	1.9	0.3	7.4	0.3	1.1	0.3	0.4	2.5
Chaharmahal and bakhtiari	69.3	3.5	1.4	3.2	1.9	4.9	0.3	9	0.2	2.3	0.3	3.5	0.2
East Azerbaijan	71.9	5.9	0.6	1.2	4.4	0.6	0.2	4.8	0.3	3.9	1.8	2.1	2.3
Esfahan	69.4	9.4	1.1	2.4	4.8	1.4	0.1	6.6	0.5	1.7	1.1	0.7	0.8
Fars	61.1	9.8	1.4	1	2.6	2.3	1	15.1	0.6	1.9	1.5	0.9	0.8
Golestan	63	7.25	1.9	2	5.5	1.1	0.05	15.1	0	1.9	1.2	0.1	0.9
Guilan	62.8	14.6	1.3	0.9	1.5	0.1	0.01	15.1	0	1.4	1.3	0.6	0.39
Hamadan	78.6	5.1	0.9	2	2	1.3	0.1	4.1	0	0.8	0.8	1.8	2.5
Hormozgan	75.8	6.08	0.76	2.4	0.9	2.37	0.13	6.5		1.5	0.76	0.1	2.7
Ilam	69	6.05	2.1	2.24	3.96	0.69	0.03	8.23	0.3	1.5	1.1	2.1	2.7
Kohgiluyeh and Boyer-Ahmad	72.6	4	1.9	1.9	2.1	1.6	0.6	6.9	0.4	2	1.8	1.9	2.3
Kerman	75.3	4.5	1.2	2.3	3	0.3	0.03	6.7	0.9	1.1	0.5	1.6	2.57
Kermanshah	74.1	3.8	1	2	3.2	0.1	0.02	8.8	0.68	2	1	1.2	2.1
Khuzestan	64.9	5.3	1	3.6	3.4	4.1	0.2	8.2	0.4	3.6	0.6	3.4	1.3
Kurdistan	66.1	5.9	1.6	2.1	3.4	1.1	0.03	8.8	0.5	2	1.6	4.37	2.5
Lorestan	77.7	7	0.8	0.9	2	0.7	0.1	8.1	0	0.4	0.6	1.3	0.4
Markazi	78.5	5.1	0.9	0.9	2.1	1	0.1	8.4	0	0.2	0.8	0.2	1.8
Mazandaran	79.17	6.5	0.3	1	1.4	1.1	0.03	6.9	0	1.1	0.4	0.3	1.8
North Khorasan	71.7	5.6	0.4	2.3	5.1	1.1	0.03	7.9	0.5	0.3	0.9	2.07	2.1
Qazvin	68	6.8	0.7	1.3	2.8	3.5	0.1	9.7	0.5	3.4	0.4	1.9	0.9
Qom	59.6	9.7	3	1.3	5.4	1.5	0.1	14	1.0	1.3	1.8	1.1	0.2
Razavi Khorasan	73.1	5.3	0.4	1.2	5.7	1.5	0.2	8.6	0.5	0.6	1.4	0.9	0.6
Semnan	73.28	4.8	0.9	1.1	6.1	0.9	0.02	10.2	0.3	0.2	1	0.2	1
Sistan and Baluchestan	52.2	4.9	1.2	2.8	8.5	1.1	0.2	18.7	0.5	3	1.3	3.6	2
South Khorasan	71.4	6.7	0.8	1.9	6.1	1.6	0.1	7.2	0.4	0.5	1.1	2	0.2
Tehran	71.2	5.9	1.3	1.6	3.6	2.1	0.4	9.6	0.3	1.8	0.6	0.6	1
West Azerbaijan	77.07	6.6	0.8	1.2	1.7	0.8	0.03	3.8	0.5	1	3	1.1	2.4
Yazd	70.4	6.2	0.8	3.2	3.4	1.1	0.1	6.8	0	0.3	0.8	4.8	2.1
Zanjan	68.4	5	0.4	2	3.5	2.6	0.1	13.1	0.3	1.4	0.9	1.3	1
Iran's average	70.26	6.33	1.08	1.81	3.55	1.56	0.17	9.13	0.35	1.53	1.09	1.59	1.58

* Source: [74], With Permission from Elsevier; Copyright© 2018; License Number 4481830942279.
** Including Iron alloys.

environmental impacts of a product/service system throughout its life cycle offering a set of results to support decision-making in the area of concern [36]. It should be noted that LCA is on the most widely used approaches for apprising the environmental aspects of renewable energy projects [37,38]. This technique has also been frequently used for assessing the environmental impacts of cane sugar production [30,138–140]. However, there is a limited number of LCA studies focused on sugar beet and beet sugar industry. For instance, in a study conducted by Renouf et al. [20], LCA of sugarcane production and processing in Australia was performed and the results obtained were compared with those of UK sugar beet and corn production in the USA with the aim of supplying sugars for ethanolic fermentation. The authors considered agricultural stage of sugarcane, sugar beet and corn as well as their processing in factories and claimed that sugarcane was advantageous in terms of energy input and GHG emissions over UK sugar beet and corn produced in the USA. This was mainly due to the utilization of bagasse as the source of energy in cane factories. Nevertheless, sugar beet showed a better environmental index in terms of acidification, eutrophication, and water consumption compared with sugarcane. Although the study did not consider a wide range of impact categories, the results also indicated that co-generation and product displacement in sugar processing stage could effectively affect the final environmental burden of the sugar industry [20].

In a different study conducted by Spoerri and Kaegi [21], environmental impacts of white beet sugar of average quality was evaluated throughout the EU during 2008–2012. The study considered the agricultural stage of sugar beet production as well as the transportation of beets and their processing in different factories in the EU. Moreover, four different impact assessment methods (i.e., in addition to ILCD, ReCiPe, Eco-scarcity, and Impact 2002 +) in addition to different allocation procedures and substitution methods were employed in order to increase the reliability of the results. The results of ILCD, ReCiPe and Eco-scarcity impact assessment methods indicated that the agricultural cultivation stage had the highest share from the total environmental burden of beet sugar life cycle following by the sugar processing stage. Nevertheless, the results of Impact 2002 + revealed that sugar processing stage had the highest contribution to the total burden imposed. Moreover, it was concluded that the allocation of environmental impacts to the different products obtained through beet sugar production should be made according to their energy content. Overall, regardless of the impact assessment method used, the following eight impact categories were determined to have the highest share of the total environmental impacts of the EU beet sugar industry: climate change, resource depletion, land use, particulate matter, eco-toxicity, human toxicity, eutrophication, and water resource depletion. Therefore, these impact categories are required to be focused on for the development of a PCR (Product Category Rules) on beet sugar in the EU [21].

Maravić et al. [141] studied the environmental impacts of using an advanced raw sugar juice purification procedure (primarily based on the implementation of Brieghel-Müller pre-limer) in a sugar plant in Serbia. In their study, only the sugar processing stage was considered and the results obtained showed that the new procedure significantly decreased the consumption of coke, limestone, and natural gas in the factory. These reductions reportedly led to reduced production costs, carbon footprint, and cumulative energy demands of raw sugar juice purification [141]. The other studies conducted on LCA of sugar beet were mainly focused on agricultural stage, and processing sugar beet to bioethanol or biogas [24–27,142–144].

5.1. Case study: Iran

In order to evaluate the impacts of the proposed solution, i.e., using WTE for power generation in beet sugar industry, two different beet sugar factories located in Iran were considered as case studies herein. More specifically, the environmental impacts of beet sugar processing were calculated and the consequent changes in environmental burdens in response to the substituting fossil electricity with a kind of waste-oriented electricity (i.e., bio-methane derived from organic fraction of MSW) for beet processing were evaluated. For this purpose, two sugar factories in Iran were considered as case studies, one in Lorestan province and the other one in Qazvin province. Lorestan sugar factory was established in 1967 based on the Polish technology with the capacity of 1500 t sugar beet/day and was upgraded by using the German technology in the last decade reaching its current capacity of 2040 t/day. Qazvin sugar factory was also established in 1967 with the capacity of 1000 t sugar beet/day and was upgraded by the French technology in the last decade reaching its current capacity of 2200 t/day.

As required by the ISO14040 series, the four main steps as: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment and 4) interpretation were considered in the LCA study [145–147].

5.1.1. Goal and scope definition, LCI (life cycle inventory), and LCIA (life cycle impact assessment)

As mentioned earlier, the goal of the present LCA study was to assess the effects of using a kind of waste-oriented electricity in sugar factories considering two factories located in Iran as case studies, while also evaluating the current situation of sugar processing and the environmental hotspots in these sugar factories. To achieve that, electricity generation through AD of organic fraction of MSWs was considered as the waste source for exploiting energy. The scope of this study (Fig. 8) included the major stages involved in (spring sown) sugar beet processing (from beet reception to sugar packaging) in both factories over the same operation period (Sep-Dec 2016). Moreover, the scope of this study included electricity generation through AD of organic fraction of MSWs. According to Fig. 8, one basic scenario and one futuristic scenario were considered as follows:

- Sc–1(Scenario 1): current (business-as-usual) situation of sugar beet processing in factories (using fossil-oriented electricity supplied by the national grid). In this scenario, both factories i.e., Lorestan and Qazvin sugar factories operated under the typical situation mentioned in Section 3, in which the following stages were performed as the beets enter the factory, i.e., beet receiving, storage and transmissions; beet washing and flume-water treatment; beet slicing; diffusion; purification; evaporation; crystallization; centrifugal separation; drying, sorting and packing. The main energy sources for the factories were natural gas, fossil electricity, fuel oil, and coke. Sugar, molasses and pellets of pulp were valuable outputs of the factory for the market while sand/stones/sugar beet tops and lime cake were mainly regarded as wastes.
- Sc–2 (Scenario 2): a futuristic scenario involving the use of electricity obtained through AD of organic fraction of MSWs as an alternative to fossil-oriented electricity consumed in the factories. In this scenario, both factories operated under the mentioned typical situation. The only difference between scenarios is that the part of energy previously supplied by fossil electricity (in Sc-1) was assumed to be substituted with electricity from waste. More specifically, the organic fraction of waste generated at the city of the factories was considered as the energy source while the potential and consequences of its converting to electricity through AD was evaluated. The main considered assumptions of the scenarios as well as description on LCI are presented at the followings:

The adopted system boundary did not embrace the waste collection and transportation since the exact location of MSW management facilities could be variable based on decision maker's policies. Moreover, it has been reported that the impact of waste collection was normally insignificant in comparison with the other life cycle stages [148–150]. In addition, it has been suggested that the impact of waste collection and transportation should be considered if new waste collection and transportation strategies are employed [151].

Likewise, the recycling process of MSWs was not included in the

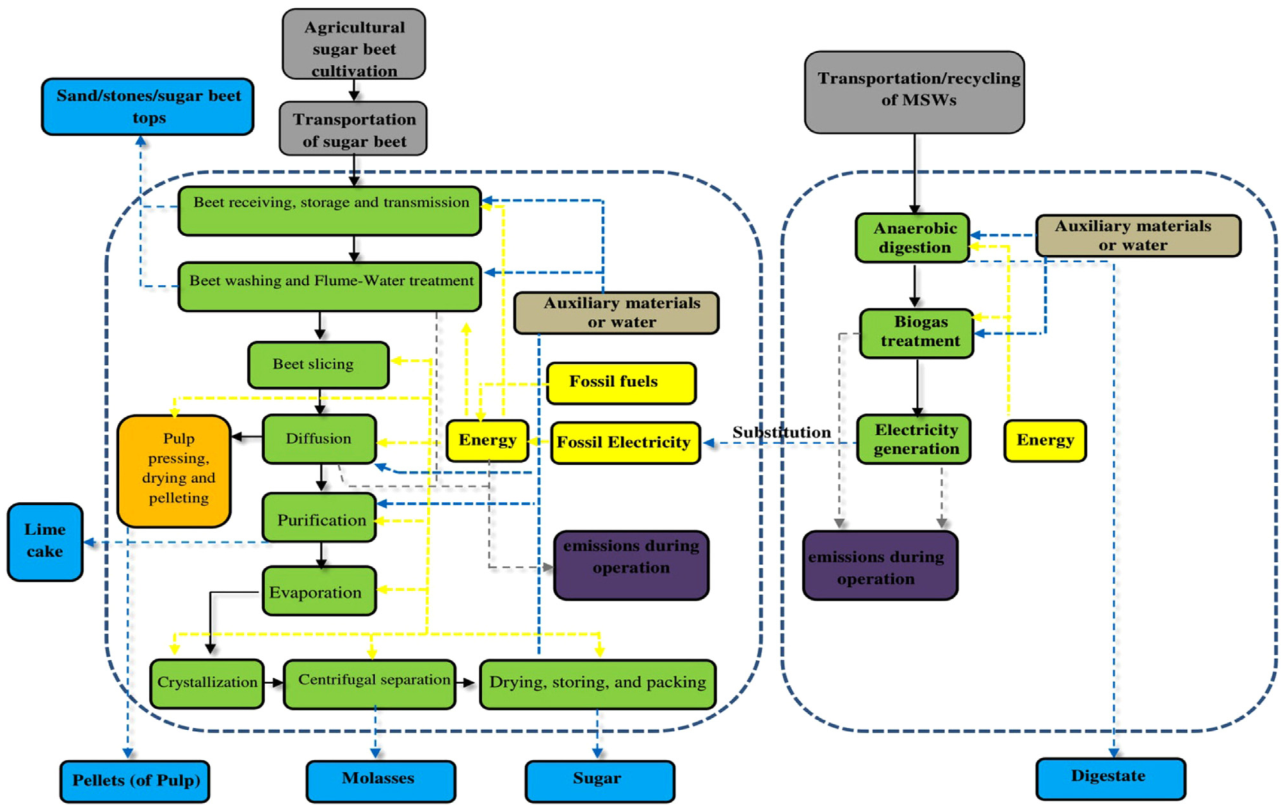

Fig. 8. Scope and system boundaries considered for the current LCA study.

adopted system boundary because the avoided environmental impacts of recycling of non-organic fraction of MSW might lead to an overestimation of the advantage of using renewable electricity generated through AD herein. It should be noted that the inclusion of recycling process could be applicable when AD of organic fraction of MSWs is combined with other waste management options for the non-organic fraction of MSW such as incineration or other waste-to-energy strategies. Moreover, the capital goods associated with sugar processing infrastructure in sugar factories as well as capital goods in MSW treatment facilities and electric power plants, were not included in the environmental profile of the developed scenarios due to the large throughput and long effective life of sugar factories, MSW treatment facilities, and power plants. Furthermore, fossil fuel transportation from the production sources to fossil power plants was taken out from the scope of the study while transportation of auxiliary materials to the factories was included in the calculations.

The functional unit (FU) of the present study was considered as 1 t of sugar beet introduced into the factory. This is a very common unit for beet sugar factories as beet sugar factories usually expresses most of the data in percentage of the processed beet mass namely % on beet (%OB) [39]. It should be noted that although FU based on “1 t of sugar produced” could have been more visually helpful in identifying the environmental balance per unit of output, the existing complication and uncertainties in the allocation procedure as well as the substitution challenges for the case studies prevented using this FU in the calculations.

In order to compile the inventory data, the foreground data set including all materials consumption as well as emissions during operation and production of outputs in sugar processing stage were collected through the course of this study. In line with that, 1) emissions of natural gas, heavy fuel oil and diesel combustion, 2) emissions during operation of different stage in the factories, 3) emissions from wastewater, and 4) emissions originated from electricity generation in electric power plants in each province -subsequently supplied through the national grid-, were taken into account. Moreover, the amount of potential biogas and electricity produced through the AD of organic fraction of MSWs were adopted from our previous work [74]. Moreover, the emissions originated from the whole WTE process were calculated based on the data presented for the only operational AD plant in Iran running on organic fraction of MSWs [152]. The background data set concerning the production and processing of inputs and energy carriers were adopted from the Ecoinvent version 3.3 database and the LCI were modeled using SimaPro 8.4.

Among the existing comprehensive and frequently used models for LCIA, Impact 2002 + method was implemented. This method has been reported to be more appropriate for assessing the environmental impacts of sugar processing since it places more emphasis on sugar factory compared with the other methods which are more focused on agricultural stage [21]. Impact 2002 + method encompasses 15 mid-point impact categories which are structured into four damage categories of human health, ecosystem quality, climate change and resources damage categories [153]. It is also worth quoting that characterization factors for climate change damage category was updated based on a time horizon of 100 years [154]. Moreover, aquatic acidification and aquatic eutrophication damage factors (from mid-point to end-point level) were updated based on Humbert et al. [155].

After investigating the environmental hotspot for the factories, a sensitivity analysis was also performed in order to determine the impact of different main source of emissions on the total damage category results. In this regards, it was assumed that further optimization by the factories would be undertaken in order to optimize the consumption of the energy inputs by increasing efficiency in order to reduce the level of the associated emissions. Moreover, each input was considered to be optimized separately since simultaneous optimization of all the energy inputs might not be practical. It is also worth quoting that optimization of coke consumption was considered through total substitution by natural gas, i.e., converting coke kilns to natural gas ones.

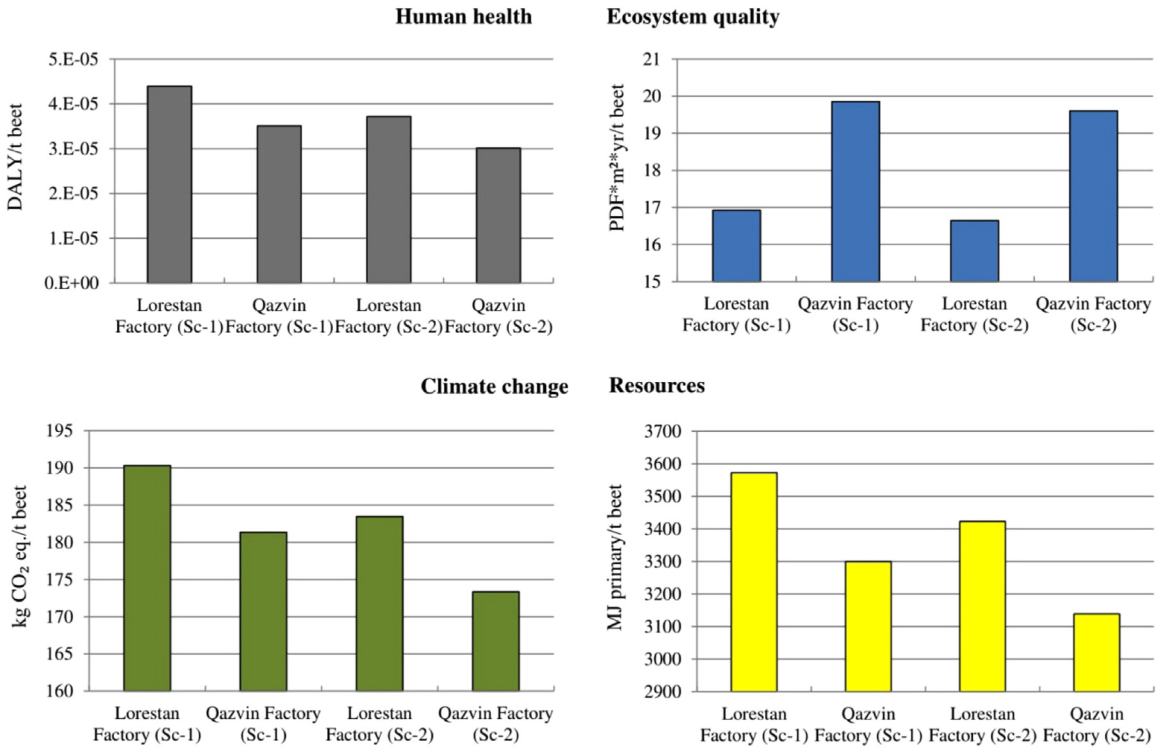

Fig. 9. Damage categories' scores for the case studies in different scenarios.

5.2. LCA results and future prospects

5.2.1. Human health damage category

Based on the results presented in Fig. 9, in the business-as-usual situation (Sc-1), the Lorestan sugar factory was suffering from a higher level of environmental burdens in this damage category, i.e., 4.39E-05 DALY (Disability-Adjusted Life Years)/ton beet compared with the Qazvin sugar factory with 3.51E-05 DALY/ton beet. In another word, the Lorestan sugar factory generated about 20% more environmental emissions in human health damage category for processing every ton of sugar beet compared with the other factory.

The results also showed that among different processes involved inside the adopted system boundary, i.e., transportation of auxiliary materials to the factory, upstream activities of different materials production, upstream activities of different fuels production, electricity generation at power plants and the process of sugar extraction, the latter or sugar processing itself (from beet receiving, storage and transmissions to the final packing) had the highest contribution to the estimated environmental burdens in this damage category with about 54% (2.37E-05 DALY/ton beet) and about 35% (1.24E-05 DALY/ton beet) for Lorestan and Qazvin sugar factories, respectively. Further inventory analysis depicted that the high share of sugar processing stage was mainly due to the emissions of SO_2 and NO_2 in the factories. More specifically, 33.25% of the emissions in human health damage category in the Lorestan sugar factory was originated from SO_2 (emission to the air), mainly emitted during the sugar extraction process because of heavy fuel oil combustion while the share of SO_2 emission in the Qazvin sugar factory was as low as 8%. More specifically, heavy fuel oil was sometimes used in the boiler house of the Lorestan sugar factory in order to start-up the boilers especially under cold weather conditions or under situations when the natural gas pressure of the local distribution grid would drop. On the contrary, heavy fuel oil was not used in Qazvin sugar factory. In addition to SO_2, the NO_2 released through natural gas combustion in boilers, mainly during sugar processing, was found responsible for 24.37% (1.07E-05 DALY/ton beet) and 29% (1.05E-05 DALY/ton beet) of the burdens in human health damage category for the Lorestan and Qazvin sugar factories, respectively. In fact, natural gas was the main source of energy used in boiler houses of both factories, however, the Lorestan sugar factory combusted more natural gas OB (79.41 m^3/ton beet) compared with the Qazvin sugar factory (72.88 m^3/ton beet).

The second contributor to human health damage category (after sugar extraction process) was the upstream activities related to natural gas production with the share of about 23% (1.01E-05 DALY/ton beet) and 25.9% (8.80E-06 DALY/ton beet) for the Lorestan and Qazvin sugar factories, respectively. Further inventory investigation showed that the release of NO_x and SO_x (emissions to the air) was responsible for 20% and 8% of the total emissions in Human health damage category in the Lorestan sugar factory. The lower natural gas consumption OB in Qazvin sugar factory led to lower amount of emissions by the upstream activities related to natural gas production in this damage category. It is also worth quoting that electricity consumption had the share of 23% (7.66E-06 DALY/ton beet) and 18% (4.8E-06 DALY/ton beet), respectively for the Lorestan and Qazvin sugar factories. Interestingly, electricity consumption per ton of beet (OB) was higher for the Qazvin sugar factory while the amount of environmental burdens caused by electricity consumption in this damage category was lower for the Qazvin sugar factory. This is mainly due to the fact that the electricity generation regime in Lorestan province had a higher level of emissions in this damage category. In better word, 1 MWh electricity generation in Lorestan province led to 1.11E-03 DALY while 1 MWh electricity generation in Qazvin province led to 5.46E-04 DALY. More specifically, in Lorestan province, 96% of each MWh electricity was generated by gas turbine power plants and the rest was supplied by hydroelectric power plants. The electricity generation pattern in Qazvin province was substantially different, i.e., 52% by steam turbines, 46% by combined cycle, and 2% by gas turbine power plants. The overall efficiencies of the combined cycle and steam turbine power plants in Qazvin province were about 43.5% and 36.5%, respectively, while the overall efficiency of gas turbine power plants in Lorestan was about 21% [156]. This difference in efficiency was the main reason behind the higher level of emissions per MWh in Lorestan province.

Table 4
The mid-point impact categories' scores for the case studies in different scenarios.

Impact category	Unit	Lorestan Factory (Sc-1)	Qazvin Factory (Sc-1)	Lorestan Factory (Sc-2)	Qazvin Factory (Sc-2)
Carcinogens	kg C_2H_3Cl eq	8.22E-01	8.09E-01	1.50E-01	2.24E-01
Non-carcinogens	kg C_2H_3Cl eq	3.21E-01	4.68E-01	2.75E-01	4.27E-01
Respiratory inorganics	kg $PM_{2.5}$ eq	5.80E-02	4.47E-02	5.12E-02	4.02E-02
Ionizing radiation	Bq C-14 eq	1.53E+02	9.45E+01	1.44E+02	7.56E+01
Ozone layer depletion	kg CFC-11 eq	2.33E-06	1.56E-06	2.25E-06	1.36E-06
Respiratory organics	kg C_2H_4 eq	5.68E-02	7.74E-02	5.48E-02	7.47E-02
Aquatic ecotoxicity	kg TEG water	1.13E+04	1.03E+04	1.11E+04	1.01E+04
Terrestrial ecotoxicity	kg TEG soil	1.81E+03	2.18E+03	1.80E+03	2.17E+03
Terrestrial acid/nutri	kg SO_2 eq	1.56E+00	1.53E+00	1.43E+00	1.44E+00
Land occupation	m^2org.arable	1.54E-01	1.49E-01	1.26E-01	1.06E-01
Aquatic acidification	kg SO_2 eq	4.96E-01	2.96E-01	4.22E-01	2.47E-01
Aquatic eutrophication	kg of PO_4^{3-}	2.05E-02	2.67E-02	1.96E-02	2.59E-02
Global warming	kg CO_2 eq	1.90E+02	1.81E+02	1.83E+02	1.73E+02
Non-renewable energy	MJ primary	3.57E+03	3.30E+03	3.42E+03	3.14E+03
Mineral extraction	MJ surplus	1.07E-01	9.53E-02	6.90E-02	5.25E-02

A closer look at inventory results at the mid-point impact category scale (i.e., sub-categories of the human health damage category) showed that heavy fuel oil consumption in the Lorestan sugar factory as well as higher amount of natural gas consumed OB in this factory, led to higher environmental burdens in respiratory inorganics, ionizing radiation and ozone layer depletion impact categories compared with the Qazvin sugar factory (Sc-1 in Table 4). The higher environmental burden in carcinogens impact category for the Lorestan sugar factory was attributed to the electricity generation regime in this province.

It is worth quoting that sugar factories generally use biocides in order to prevent microbiological action in the diffusion juice. For many years, formalin was used as one of the most popular biocides in sugar industry for this purpose. However, its application has been discontinued in some countries and is expected to be discontinued in the remaining countries due to many environmental risks [39]. Accordingly, decreasing formalin consumption in the Qazvin sugar factory could also be regarded as one of the main priorities since the emissions of formaldehyde to air was responsible for the higher environmental impact of the Qazvin sugar factory in Non-carcinogens and respiratory organics impact categories. In this context, alternative biocides could be considered such as monochloramine which has been proven to be environmentally-favorable compared with formalin [157].

The results of the futuristic scenario, i.e., Sc-2 revealed that employing renewable (waste-oriented) electricity in both factories would reduce the environmental burdens in human health damage category (Fig. 9). More specifically, using renewable electricity in the Lorestan sugar factory could reduce the damage to the human health by 15.41% while the reduction rate was 14.11% for the Qazvin sugar factory. This is mainly due to the fact that 1 MWh electricity generation in Lorestan province showed 50% higher environmental burden in human health damage category compared with 1 MWh electricity generation in Qazvin province. Even by considering the fact that electricity consumption per ton of beet in the Qazvin sugar factory was 41% higher than that of the Lorestan sugar factory and consequently higher amounts of renewable electricity could be substituted in the Qazvin sugar factory, the overall reduction in environmental burden was higher for the Lorestan Province. This was ascribed to the higher environmental burdens in human health damage category caused by the less favorable electricity generation pattern in Lorestan province. The results of inventory analysis showed that using 1 MWh renewable electricity through AD of MSWs in Lorestan province could potentially reduce the amount of SO_2 (with the impact of 5.32E-04 DALY/MWh) and NO_x (with the impact of 2.57E-04 DALY/MWh) emissions by 97.6% and 58.4%, respectively. The situation was the same for Qazvin province in which the amount of SO_2 (with the impact of 2.09E-04 DALY/MWh) and NO_x (with the impact of 1.67E-04 DALY/MWh) could be reduced by 94% and 36% respectively, by using renewable electricity.

The inventory results for the mid-point impact categories (i.e., sub-categories of human health damage category) showed that employing renewable electricity could potentially reduce the environmental burdens in all the mid-point impact categories for both factories especially for carcinogens impacts (Sc-2 in Table 4). More specifically, using renewable electricity could significantly reduce the emission of aromatic hydrocarbons (attributed to the upstream activities of the natural gas used in power plants) and consequently reduce carcinogens impacts significantly.

5.2.2. *Ecosystem quality damage category*

When studying Sc-1 from the ecosystem quality damage category point of view (Fig. 9), the Qazvin sugar factory showed a higher environmental burden, i.e., 19.9 PDF*m^2 *yr (Potentially Disappeared Fraction*m^2 *year)/ton beet compared with the business-as-usual production scenario in the Lorestan sugar factory, i.e., 16.90 PDF*m^2*yr/ton beet. The results obtained also showed that the upstream activities related to natural gas production had the highest share from the total damage posed to ecosystem quality with the shares of 60.15% (11.97 PDF*m^2*yr/ton beet) and 81.59% (13.79 PDF*m^2*yr/ton beet) for Qazvin and Lorestan sugar factories, respectively. Emissions of Aluminum to the soil (upstream activities of natural gas production) were responsible for more than 50% of the emissions in ecosystem quality damage category. Nevertheless, what made the Qazvin sugar factory worse than the other factory in this damage category was the transportation effect. More specifically, transportation of auxiliary materials to the factory was the second contributor to the ecosystem quality damage category (after natural gas) with the share of 26.89% (5.33 PDF*m^2*yr/ton beet) for Qazvin factory while the share of transportation from the ecosystem quality damage category for the Lorestan sugar factory was very low standing at 2.52% (0.43 PDF*m^2*yr/ton beet). Further inventory analysis showed that the transportation of limestone to the factory with the share of 90.1% (4.8 PDF*m^2*yr/ton beet) followed by the transportation of coke for the lime kiln with the share of 9.4% (0.5 PDF*m^2*yr/ton beet) were responsible for such high impact for Qazvin sugar factory. In fact, the transportation distances for limestone and coke to the Qazvin factory were about 273 km and 481 km; much higher than those recorded for the Lorestan sugar factory (limestone transportation distance of 20 km and no coke transportation since no coke was consumed). It is also worth quoting that although the Qazvin sugar factory consumed coke and accordingly, higher environmental emissions to the air would be expected, however, opposite observations were made owing to the fact that coke combustion took place at lime kilns where the entire exhaust gases were vented to raw juice in the purification step resulting the removal of the majority of air pollutants [39].

A detailed investigation on the mid-point impact categories (i.e.,

sub-categories of the ecosystem quality damage category) illustrated that the transportation of limestone and coke for the lime kiln in the Qazvin sugar factory led to higher environmental burdens in terrestrial ecotoxicity and aquatic eutrophication impact categories (Sc-1 in Table 4). Although Lorestan sugar factory showed higher environmental burden in aquatic ecotoxicity, terrestrial acidification/nitrification, land occupation, and aquatic acidification impact categories (mainly due to higher amounts of natural gas consumption and heavy fuel oil per ton of beet), the Qazvin sugar factory showed an overall higher impact in ecosystem quality damage category mainly due to higher environmental impact in terrestrial ecotoxicity impact category. Therefore, further optimization of transportation distances for limestone and coke in the Qazvin sugar factory could be another important priority for this factory.

The results of Sc-2 in ecosystem quality damage category (Fig. 9) showed that using renewable bioelectricity could potentially decrease the environmental burden in this damage category for both sugar factories. By employing renewable bioelectricity, reduction rates of 1.54% and 1.49% in ecosystem quality damage category could be expected for the Lorestan and Qazvin sugar factories, respectively. The results of inventory analysis showed that these reductions would mainly be attributed to decrements in NO_x and SO_x emissions (to the air originated from fossil fuels combustion at power plants), as well as aluminum emissions (to the air/soil/water originated by upstream activity of fossil fuel production-fossil fuel used in power plants-, i.e., extraction of petroleum). More specifically, using 1 MWh electricity from AD of MSWs could potentially reduce NOx for the Lorestan and Qazvin sugar factories by 10.95 PDF*m^2*yr and 4.35 PDF*m^2*yr, respectively. Moreover, if 1 MWh fossil-oriented electricity were replaced by renewable electricity, the reduction rates for aluminum emissions (to the air/soil/water) would be 14.9 and 9.6 PDF*m^2*yr while SOx reduction (emission to the air) would be 10 and 3.8 PDF*m^2*yr for the Lorestan and Qazvin sugar factories, respectively.

A more detailed inventory analysis in the mid-point level (i.e., subcategories of the ecosystem quality damage category) revealed that using electricity obtained by AD of MSWs could potentially reduce the environmental burdens in all the mid-point impact categories for both factories especially in land occupation and aquatic acidification impact categories (Sc-2 in Table 4). In another word, using renewable electricity could significantly reduce the land occupation attributed to the upstream activities of electricity generation in power plants and consequently reduce its final impact. Likewise, substituting fossil electricity with renewable one could reduce NO_x and SO_x emissions to the air originated from fossil fuels combustion at power plants and consequently lower the aquatic acidification impact. It is worth noting that the emissions of aluminium to water and soil were attributed to the upstream activity of fossil fuel production-fossil fuel used in power plants-, i.e., extraction of petroleum, and were responsible for the high value of aquatic ecotoxicity and terrestrial ecotoxicity impact categories which could be also reduced through the renewable electricity usage.

5.2.3. Climate change damage category

This damage category has attracted a considerable deal of attention globally owing to the diverse unfavorable impacts of climate change on various aspects of life on the planet. Based on the results obtained herein (Sc-1 Fig. 9); the Lorestan sugar factory had a higher contribution to the climate change damage category with a value of 190.32 kg CO_{2eq}/ton beet implying 4.7% higher contribution compared with the Qazvin sugar factory (with a value of 181.35 kg CO_{2eq}/ton beet). Further investigation on the contribution of different factors showed that the process of sugar extraction had the highest share in environmental emissions in this damage category with about 80% (152.59 kg CO_{2eq}/ton beet) and about 77% (140.6 kg CO_{2eq}/ton beet) for the Lorestan and Qazvin sugar factories, respectively. A detailed inventory analysis depicted that 99% of the emissions in climate change damage category in the Lorestan sugar factory was originated from CO_2 emissions mainly during the sugar extraction process as a result of natural gas and fuel oil combustion. The lower amount of natural gas consumption OB and the absence of heavy fuel oil in the fuel basket, caused lower amount of climate change impacts by the Qazvin sugar factory. As mentioned earlier, although the Qazvin sugar factory used coke in its lime kiln, the resultant air pollution including a large amount of CO_2 were vented to the raw juice in the purification step and most of the air pollutants were removed. In fact, the CO_2 gas was used in order to finally precipitate the lime as calcium carbonate.

Exactly similar to human health damage category, the second contributor to climate change damage category (following sugar extraction process) was the upstream activities of natural gas production with a share of about 14.9% (28.51 kg CO_{2eq}/ton beet) and 13.6% (24.76 kg CO_{2eq}/ton beet) for the Lorestan and Qazvin sugar factories, respectively. It is also worth quoting that after upstream activities of natural gas production, electricity consumption in both factories had the highest share from the total climate change effects. The results also showed that 1 MWh electricity generation in Lorestan province produced more than 30% higher GHG emissions compared with 1 MWh electricity generation in Qazvin province. Since climate change damage category encompasses only GW (global warming) impact category with conversion factor of 1 (from GW mid-point to climate change endpoint), the inventory analysis showed similar results as climate change damage category.

Based on the results obtained herein for Sc-2 (Fig. 9), using electricity from AD of MSWs could potentially help with reducing climate change impacts by 4% and 4.4% for the Lorestan and Qazvin sugar factories, respectively. This could be very promising since Iran is internationally committed to reduce its GHGs emissions by 4% by the year 2030. In fact, one of the main powerful aspects of using renewable energies is the reduction of GHG emissions, especially CO_2 emissions by reducing the share of geologic CO_2 emissions. In this regards, generating 1 MWh renewable electricity could potentially reduce CO_2 emissions by 939.7 kg CO_{2eq} for Lorestan and 643.7 kg CO_{2eq} for Qazvin provinces. Reductions would also be considerable in case of methane emissions; more specifically, 1 MWh renewable electricity could potentially reduce CH_4 emissions by 57.66 kg CO_{2eq} for the Lorestan and 34.36 kg CO_{2eq} for the Qazvin sugar factories. There have been many studies on assessing the GHG emissions (and consequently climate change impacts) of electricity generation through AD of organic fraction of MSWs [74,158–162]. These studies have concluded that the utilization of biogas generated through AD of organic fraction of MSWs for electricity generation could potentially make credits for electricity generation in view of GHG emissions and climate change. The differences observed in net GHG emissions reductions in these studies could be attributed to the source of data used, type of electricity mix in the country of study, scopes and assumptions of their study, and the modeling approach employed.

5.2.4. Resources damage category

The results of resources damage category (Sc-1 Fig. 9) revealed that the Lorestan sugar factory consumed 7.6% more primary energy compared with the Qazvin sugar factory (Sc-1). More specifically, in the Lorestan sugar factory, 3572 MJ primary energy was consumed for processing each ton of beet while this value stood at 3299 MJ primary/ton beet for the Qazvin sugar factory. Further inventory analysis showed that natural gas consumption had the highest contribution to resources damage category with a share of 90% (3233.20 MJ primary/ton beet) for the Lorestan sugar factory and 85% (2807 MJ primary/ton beet) for the Qazvin sugar factory. Following natural gas, consumption of heavy fuel oil had the second contribution to resources damage category in the Lorestan sugar factory (4%; 161.24 MJ primary/ton beet) while coke had the second contribution to this damage category in the Qazvin sugar factory (7.24%; 239.02 MJ primary/ton beet). Obviously, the higher amount of natural gas consumption per ton of beet in the

Table 5
Results of optimization of environmental hotspots in Lorestan sugar factory.

Damage category	Unit	Lorestan Factory (Sc-1)	1% natural gas optimization	1% Fuel oil optimization	1% Electricity optimization	1% fossil electricity substitution by renewable electricity
Human health	DALY	4.39E-05	4.37E-05	4.38E-05	4.38E-05	4.38E-05
Ecosystem quality	PDF*m^2*yr	16.926	16.777	16.920	16.922	16.923
Climate change	kg CO_2 eq	190.31	188.59	190.22	190.24	190.25
Resources	MJ primary	3572.69	3540.35	3570.9	3571.16	3571.19

Lorestan sugar factory led to a higher effect on resources damage category compared with the Qazvin sugar factory. It should also be noted that electricity consumption in both factories had the highest share from the total impacts on resources following natural gas and heavy fuel oil/coke consumption. The results also showed that 2.21E4 MJ primary was used to generate 1 MWh electricity in Lorestan province while 1 MWh electricity generation in Qazvin province only consumed 1.4E4 MJ primary. This simply shows the necessity of employing renewable energies for electricity generation in Lorestan province. Further inventory analysis in the mid-point level (Sc-1 in Table 4) showed that the Lorestan sugar factory imposed higher impacts on the primary resources in both non-renewable energy and mineral extraction mainly due to higher consumption of natural gas, heavy fuel oil, and its electricity generation pattern.

Based on the results of resources damage category (Sc-2 Fig. 9), utilizing renewable electricity could potentially reduce the primary energy consumption by 4.18% and 4.87% in the Lorestan and Qazvin sugar factories, respectively. Substituting fossil-based electricity with renewable one would lead to a reduction in natural gas consumption as the main fossil resource used in gas turbine power plants in Lorestan province with the value of 1.96E04 MJ primary/MWh (while the total value in resource damage category was calculated as 2.21E04 MJ primary/MWh). Likewise, natural gas consumption was the main fossil resource used in steam turbine, combined cycle, and gas turbine power plants in Qazvin province (with the value of 1.08E04 MJ primary/MWh out of the total value of 1.4E04 MJ primary/MWh in resource damage category). Due to different electricity pattern in Qazvin province and higher efficiency in electricity generation, the amount of natural gas consumption and the total impacts on resources were lower in Qazvin province (at about 36% lower total impacts in resources damage category) vs. Lorestan province. It is also worth quoting that since electricity consumption per ton of beet was about 41% higher in the Qazvin sugar factory, therefore, the reduction rate in resources damage category by using renewable electricity was higher for this sugar factory compared with the Lorestan sugar factory.

A more detailed inventory analysis in the mid-point level (i.e., subcategories of resources damage category) revealed that using electricity from AD of MSWs could reduce the environmental burdens in both impact categories (Sc-2 in Table 4). As expected, the environmental burdens of the non-renewable energy impact category would be reduced in response to utilizing renewable electricity. More interestingly, the environmental burden in mineral extraction impact category would also be reduced by 35.5% and 44.8% in Lorestan and Qazvin sugar factories, respectively. This was mainly due to the reduction in nickel extraction as well as copper extraction which occurred by Ferronickel production and copper mine operations, respectively. These processes are the upstream activities of natural gas production – natural gas is used as the main fossil resource in power plants.

5.3. Overall assessment and sensitivity analysis

Overall, the results of different damage categories showed that the Lorestan sugar factory potentially posed a higher level of risk to human health (20%) and generated higher levels of emissions contributing to the climate change (4.7%) and resources damage categories (7.6%) compared with the Qazvin sugar factory (Lorestan sugar factory also generated 15.01% less environmental emissions in ecosystem quality damage category). It should be noted that one could hypothesize that such amount of higher emissions may be associated with higher sugar products. To investigate this hypothesis and based on the results obtained herein, the Lorestan sugar factory produced about 12% more sugar and 13% more beet pulp, but about 48% less molasses per ton of beet compared with the Qazvin sugar beet factory. Economically, the Lorestan sugar factory showed a 9.58% higher gross income compared with its counterpart. On the other hand, as mentioned earlier, the Lorestan sugar factory suffered from 20%, 4.7% and 7.6% higher emissions in different mentioned damage categories. The overall situation might seems economically favorable for the Lorestan sugar factory since no cost or taxes are enforced for the emissions in the business-as-usual scenario, however, the overall economic superiority might be jeopardized if emissions taxes would be enforced in any futuristic scenarios.

Based on the results obtained for different damage categories, energy inputs were the main sources of environmental burdens in all damage categories. In this regard, natural gas, heavy fuel oil, coke, and electricity from conventional power plants could be recognized as important sources of environmental burdens. Therefore, a sensitivity analysis was performed assuming that 1% optimization in the consumption of each input would be achieved in each factory. The optimization was considered through increasing the efficiency of inputs consumption. This means that a reduction in the input consumption is expected per ton of beet. Moreover, each input was considered to be optimized separately since simultaneous optimization of all the energy inputs might not be logical. Tables 5, 6 show the results of 1% optimization of the selected energy inputs in the Lorestan and Qazvin sugar factories, respectively.

Based on the sensitivity analysis results, 1% optimization of natural gas consumption in the Lorestan sugar factory (Table 5) could potentially reduce the environmental burdens by 0.5% in human health, by 0.88% in ecosystem quality, by 0.91% in climate change, and by 0.90% in resources damage categories (overall 3.2% reduction in environmental burdens). These reductions could be at 0.58%, 0.66%, 0.91%,

Table 6
Results of optimization of environmental hotspots in Qazvin sugar factory.

Damage category	Unit	Qazvin Factory (Sc-1)	1% natural gas optimization	substituting coke kiln with natural gas kiln in	1% Electricity optimization	1% fossil electricity substitution by renewable electricity
Human health	DALY	3.51E-05	3.49E-05	3.42E-05	3.50E-05	3.50E-05
Ecosystem quality	PDF*m^2*yr	19.851	19.721	20.024	19.848	19.849
Climate change	kg CO_2 eq	181.352	179.700	180.024	181.268	181.271
Resources	MJ primary	3299.69	3271.61	3227.58	3298.02	3298.08

and 0.85% in human health, ecosystem quality, climate change and resources damage categories, respectively, for the Qazvin sugar factory (Table 6) (overall 3% reduction in environmental burdens).

One percent optimization of heavy fuel oil consumption in the Lorestan sugar factory (Table 5) could potentially lead to a reduction in the environmental burdens to human health (by 0.28%), ecosystem quality (by 0.03%), climate change (by 0.1%), and resources (by 0.1%) damage categories. It should be noted that since fuel oil was not consumed frequently, using biomass could potentially be an appropriate approach to substitute a higher percentage of fuel oil in the Lorestan sugar factory and to consequently reduce higher the amounts of environmental burdens especially in human health damage category since biofuels are generally sulfur-free or contain low-sulfur amounts and do not lead to SO_2 and SO_3 emissions during their combustion. Moreover, the sensitivity results also showed that substituting all the coke consumed by natural gas (in the Qazvin sugar factory) could reduce the environmental burdens (Table 6) in human health (by 2.59%), climate change (by 0.73%), and resources (by 2.19%) damage categories while could potentially increase ecosystem quality impacts (by 0.87%).

The results also showed that 1% optimization in electricity consumption in the Lorestan sugar factory (Table 5) could potentially lower the environmental impacts in different damage categories, i.e., by 0.17% in human health, by 0.02% in ecosystem quality, by 0.04% in climate change, and by 0.04% in resources damage categories (overall 0.27% reduction in environmental burdens). The reduction rate was approximately similar for the Qazvin sugar factory (Table 6) in which 0.18% reduction in human health, 0.02% reduction in ecosystem quality, 0.05% reduction in climate change, and 0.05% reduction in resources damage categories (overall 0.3% reduction in environmental burdens) could be achieved.

The sensitivity analysis for implementing renewable electricity in the factories showed that for each percentage substitution in fossil-oriented electricity by renewable ones, the environmental impacts for the Lorestan sugar factory could be reduced by 0.15%, 0.02%, 0.04%, and 0.04% in human health, ecosystem quality, climate change, and resources damage categories, respectively, (Table 5). The reduction rates for the Qazvin sugar factory (Table 6) stood at 0.14%, 0.01%, 0.04%, and 0.05% in human health, ecosystem quality, climate change, and resources damage categories, respectively. It is also worth quoting that when implementing renewable electricity in the factories, no reduction in electricity consumption would take place while when optimizing 1% electricity consumption, it was considered that 1% reduction in electricity consumption was achieved. This could be the main reason behind lower reduction potentials for 1% substituting fossil electricity by renewable electricity in comparison with 1% optimization in electricity consumption. On the other hand, it should be noted that the extent of optimization is generally limited while on the contrary, the extent of substitution would be theoretically limitless and practically all the electricity consumed in the factories could be substituted by renewable electricity.

It finally should be mentioned that producing renewable electricity through AD of organic fraction of MSWs would be a two-sided approach; one is reducing the share of fossil electricity generation in the electricity pattern. In light of that, Rajaeifar et al. [74] estimated the electricity generation potential (technical potential) of 7.2 MW and 6.4 MW for Lorestan and Qazvin provinces, respectively (only from AD of organic fraction of MSWs). Consequently, these potentials could reduce the GHG emissions by 987 kg CO_{2eq}/MWh for Lorestan and 675 kg CO_{2eq}/MWh for Qazvin provinces.

The other and more important side of using renewable electricity generated by AD of organic fraction of MSWs would be to reduce the environmental emissions which could be imposed on the environment by landfilling huge amounts of waste when not converted into energy. It should be mentioned that landfilling of waste is still the commonly-used management option in Iran and is considered as main environmental challenges/concerns faced by the country [83].

Another important issue for both factories was the huge amount of carbonation-lime residues (lime cake) generated at the sugar processing stage. Accumulation of lime cake in the lime ponds of the factories or open dumping sites is not environmentally friendly [39]. Nevertheless, these factories just dumped these huge amounts of lime cake outside the factories (this is a common method for handling lime cake in all beet sugar factories in Iran). This huge amount of lime cake could be an appropriate source of lime fertilizer which could be economically beneficial for the factories while, its dumping could be harmful to the environment and the least effect would be the occupation of arable lands adjacent to the factories. In this regard, it has been estimated that 30.42 kg and 51.56 kg lime fertilizer per ton of beet could be produced from the huge amounts of lime cake generated in the Lorestan and Qazvin sugar factories, respectively.

6. Conclusions and future prospects

The high amounts of fossil energy used in the processing stage of sugar beet as well as the environmental threats posed throughout the life cycle of sugar production (as an old challenge) are sustainability challenges faced by this sub-sector. While many efforts have been made to audit and optimize main energy flows or extract value-added products from sucrose, little attempts have been made on the use of WTEs as sources of power during sugar production (except for well-known bagasse case studies).

Overall, the results of the present work showed that the environmental impacts in human health and climate change resources damage categories are mainly dominated by the processing of sugar (emissions during sugar processing) in the factories, while the upstream activities of natural gas production were responsible for the majority of environmental burdens in ecosystem quality damage category. Natural gas consumption during sugar beet processing is also responsible for the main impacts on resources damage category. In such context, energy inputs were generally found as the main sources of environmental burdens in all damage categories.

The results also revealed that implementing waste-oriented electricity (obtained through AD of organic fraction of MSWs) instead of fossil-based electricity used in beet sugar factories could potentially reduce the environmental burdens in all the damage categories, i.e., 14.11–15.41% in human health, 1.49–1.54% in ecosystem quality, 4–4.4% in climate change and 4.18–4.87% in resources damage categories. Moreover, since accumulating lime cake in lime ponds of sugar factories or open dumping sites (used for lime cake treatment strategy) is not environmentally-friendly, it is suggested to further process this valuable residues to produce value-added products such as agricultural fertilizer. Future works should be focused on assessing the potential of other WTE technologies like incineration and pyrolysis/gasification of MSWs in order to provide the factories with renewable energy carriers. Moreover, using the other alternative energy sources, e.g., solar, wind, geothermal, and modern biomass technologies in order to substitute a portion of fossil fuel used in sugar industry should also be investigated. In addition to those, substantive research studies are needed on different novel applications of lime cake and their LCA in comparison with the current unfavorable treatment methods, i.e., accumulation of lime cake in lime ponds of the factories or open dumping.

Acknowledgments

The authors would like to thank Sugar Beet Seed Institute (SBSI), Agricultural Biotechnology Research Institute of Iran (ABRII), Biofuel Research Team (BRTeam), and Iranian Biofuel Society (IBS) for supporting this study.

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